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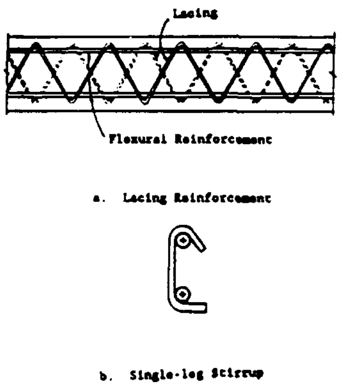
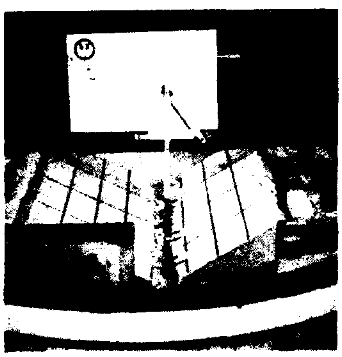
US Army Corps of Engineers

LACING VERSUS STIRRUPS - AN EXPERIMENTAL STUDY OF SHEAR REINFORCEMENT IN BLAST-RESISTANT STRUCTURES





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13. ABSTRACT *(Maximum 200 words)*

Design guides and manuals for blast-resistant reinforced concrete structures require the use of shear reinforcement (lacing bars or stirrups) to improve performance in the large-deflection region of response. It is generally known that the cost of using lacing reinforcement is considerably greater than that of using single-leg stirrups due to the more complicated fabrication and installation procedures. A thorough study of the role of shear reinforcement in structures designed to resist blast loadings or undergo large deflections has never been conducted. A better understanding of the effects of shear reinforcement on large deflection behavior will allow the designer to determine the benefits of using shear reinforcement and to determine which type is most desirable for the given structure. This capability will result in more efficient or effective designs as reflected by lower cost structures. Results of an experimental study comparing the effects of stirrups and lacing are presented.

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PREFACE

This study was conducted by the US Army Engineer Waterways Experiment Station (WES) under the joint sponsorship of the Laboratory Discretionary Research and Development Program at WES and the Department of Defense Explosives Safety Board.

The work was conducted at WES in the Structures Laboratory under the supervision of Messrs. Bryant Mather, Chief, James T. Ballard, Assistant Chief, and Dr. Jimmy P. Balsara, Chief, Structural Mechanics Division (SMD). Mr. Stanley C. Woodson, SMD, performed the study and prepared this report.

Dr. Robert W. Whalin was the Director of WES. COL Leonard G. Hassell, EN, was Commander and Deputy Director.

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CONVERSION FACTORS, NON-SI TO SI (METRIC) UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
degrees (angle)	0.01745	radians
feet	0.3048	metres
inches	25.4	millimetres
kips (force) per square inch	6.894757	megapascals
pounds (force)	4.448222	newtons
pounds (force) per square inch	0.006894757	megapascals

LACING VERSUS STIRRUPS - AN EXPERIMENTAL STUDY OF SHEAR REINFORCEMENT IN BLAST-RESISTANT STRUCTURES

PART I: INTRODUCTION

Background

General.

1. Design guides and manuals for blast-resistant reinforced concrete structures require the use of shear reinforcement to improve performance in the large-deflection region. Shear reinforcement used in blast-resistant design usually consists of either lacing bars or single-leg stirrups (Figure 1.1). Lacing bars are reinforcing bars that extend in the direction parallel to the principal reinforcement and are bent into a diagonal pattern between mats of principal reinforcement. The lacing bars enclose the transverse reinforcing bars which are placed outside the principal reinforcement. It is generally known that the cost of using lacing reinforcement is considerably greater than that of using single-leg stirrups due to the more complicated fabrication and installation procedures.

2. In the design of conventional structures, the primary purpose of shear reinforcement is to prevent the formation and propagation of diagonal tension cracks. The shear reinforcement requirements for conventional structures are based on much research and data from static beam tests. Much less study has been devoted to examining the role of this type of reinforcement in slabs under distributed dynamic loads, especially in the large-deflection region of response. In blast-resistant design, structures are typically designed to survive only one loading and relatively large deflections are acceptable as long as catastropic failure is prevented.

3. Some type of shear reinforcement in the form of lacing or stirrups is required by applicable design manuals for almost all blast resistant structures. A considerable amount of relatively recent (1970's and 1980's) data from various tests conducted on slabs indicate that the shear reinforcement design criteria typical of current design manuals may be excessive. This data base (Woodson, 1990) primarily consists of slab tests conducted to investigate parameters other than shear reinforcement details. A thorough study of the role of shear reinforcement (stirrups and lacing) in structures designed to resist blast loadings or undergo large deflections has never been conducted. A better understanding of the mechanics associated with the effects of shear reinforcement on the large-deflection behavior of slabs will allow the designer to determine the benefits of using shear reinforcement and to determine which type is most desirable for the given structure. This capability will result in more efficient or effective designs as reflected by lower cost structures without the loss of blast resistant capacity. Summaries of prominent design guides follow.

The Tri-Service Technical Manual 5-1300.

4. The recently revised Tri-Service Manual (Department of the Army, the Navy, and the Air Force; 1990) is the most widely used manual for structural design to resist blast effects. Its Army designation is TM 5-1300, for the Navy it is NAVFAC P397, and for the Air Force it is AFM 88-22. For convenience, it will be referred to as TM 5-1300.

5. Considering the resistance-deflection relationship for flexural response of a reinforced concrete element, Section 4-9.1 of the manual states that, within the range following yielding of the flexural reinforcement, the

compression concrete crushes at a deflection corresponding to 2 degrees* support rotation. This crushing of the compression concrete is considered to be "failure" for elements without shear reinforcement. For elements with shear reinforcement (single-leg stirrups or lacing reinforcement) which properly tie the flexural reinforcement, the crushing of the concrete results in a slight loss of capacity since the compressive force is transferred to the compression reinforcement. As the reinforcement enters into its strain-hardening region, the resistance increases with increasing deflection. Section 4-9.1 of the manual states that single-leg stirrups will restrain the compression reinforcement for a short time into its strain hardening region until failure of the element occurs at a support rotation of 4 degrees. It further states that lacing reinforcement will restrain the flexural reinforcement through its entire strain-hardening region until tension failure of the principal reinforcement occurs at a support rotation of 12 degrees. TM 5-1300 distinguishes between a "close-in" design range and a "far" design range for purposes of predicting the mode of response. In the far design range, the distribution of the applied loads is considered to be fairly uniform and deflections required to absorb the loading are comparatively small. Section 4-9.2 states that non-laced elements are considered to be adequate to resist the far-design loads with ductile behavior within the constraints of the allowable support rotations previously discussed. Section 4-9.3 states that the design of the element to undergo deflections corresponding to support rotations between 4 and 12 degrees requires the use of laced reinforcement. An exception is when the element has sufficient

*A table of factors for converting non-SI units of measurement used in this report to SI (metric) units is presented on page 3.

lateral restraint to develop in-plane forces in the tensile-membrane region of response. In this case, Section 4-9.2 states that the capacity of the element increases with increasing deflection until the reinforcement fails in tension. A value of support rotation is not given here, but one might deduce that a support rotation of 12 degrees is intended since it is the value given in Section 4-9.1 for tension failure of the reinforcement in a laced slab. However, a value of 8 degrees is given elsewhere in the manual as a limit of support rotation for elements containing stirrups and experiencing tensile membrane behavior.

6. Section 4-9.3 of TM 5-1300 discusses ductile behavior in the close-in design range. Again, the maximum deflection of a laced element experiencing flexural response is given as that corresponding to 12 degrees support rotation. This section states the following:

> "Single leg stirrups contribute to the integrity of a protective element in much the same way as lacing, however, the stirrups are less effective at the closer explosive separation distances. The explosive charge must be located further away from an element containing stirrups than a laced element. In addition, the maximum deflection of an element with single leg stirrups is limited to 4 degrees support rotation under flexural action or 8 degrees under tension membrane action. If the charge location permits, and reduced support rotations are required, elements with single leg stirrups may prove more economical than laced elements."

7. Section 4-32 further states:

> "... Also, the blast capacities of laced elements are greater than for corresponding (same concrete thickness and quantity of reinforcement) elements with single leg stirrups. Laced elements may attain deflections corresponding to 12 degrees support rotation whereas elements with single leg stirrups are designed for a maximum rotation of 8 degrees. These non-laced elements must develop tension membrane action in order to develop this large support rotation. If support conditions do not permit tension membrane action, lacing reinforcement must be used to achieve large deflections."

8. It is implied throughout TM 5-1300 that laced elements may attain support rotations of 12 degrees whether they are restrained against lateral movement or not. The manual also implies that a non-laced element may only achieve a maximum support rotation of 8 degrees when it is restrained against lateral movement.

9. In addition to being required for large-deflection behavior, lacing reinforcement is required in slabs subjected to blast at scaled distances less than 1.0 ft/(lbs$^{1/3}$). Section 4-9.4 of TM 5-1300 indicates that lacing reinforcement is required due to the need to limit the effects of post-failure fragments resulting from flexural failure. It is implied that the size of failed sections of laced elements is fixed by the location of the yield lines, whereas the failure of an unlaced element results in a loss of structural integrity and fragments in the form of concrete rubble. Section 4-22 discusses the use of single-leg stirrups in slabs at scaled distances between 1.0 and 3.0. Support rotations in slabs with stirrups are limited to 4 degrees in the close-in design range unless support conditions exist to induce tensile membrane behavior. In addition, a non-laced element designed for small deflections in the close-in design range is not reusable and, therefore, cannot sustain multiple incidents.

Army Technical Manual 5-855-1.

10. TM 5-855-1 (Department of the Army, 1986) is intended for use by engineers involved in designing hardened facilities to resist the effects of conventional weapons. The manual includes design criteria for protection against the effects of a penetrating weapon, a contact detonation, or the blast and fragmentation from a standoff detonation.

11. Chapter 9 of TM 5-855-1 discusses the design of shear reinforcement. Being published in 1986, the shear reinforcement criteria presented are primarily based on the guidance of ACI 318-83 (American Concrete Institute, 1983) with consideration of available test data. The maximum allowable shear stress to be contributed by the concrete and the shear reinforcement is given as $11.5(f_c')^{1/2}$ for design purposes as compared to $8(f_c')^{1/2}$ given by ACI 318-83. An upper bound to the shear capacity of members with web reinforcing is given as that corresponding to a 100 percent increase in the total shear capacity outlined by ACI 318-83 and consisting of contributions from the concrete and shear reinforcing. An important statement concerning shear reinforcement in one-way slabs and beams is given in Section 9-7 and reads as follows:

> "Some vertical web reinforcing should be provided for all flexural members subjected to blast loads. A minimum of 50-psi shear stress capacity should be provided by shear steel in the form of stirrups. In those cases where analysis indicates a requirement of vertical shear reinforcing, it should be provided in the form of stirrups."

12. TM 5-855-1 states that shear failures are unlikely in normally constructed two-way slabs, but that the possibility of shear failure increases in some protective construction applications due to high-intensity loads. Shear is given as the governing mode of failure for deep, square, two-way slabs. In the event shear capacity is required above that provided by the concrete alone, additional strength can be provided in the form of vertical and/or horizontal web reinforcing. For beams, one-way slabs, and two-way slabs, the manual recommends a design ductility ratio of 5.0 to 10.0 for flexural design.

Army Engineer Technical Letter 1110-9-7.

13. ETL 1110-9-7 (Department of the Army, 1990) is a recent guide developed to supplement TM 5-855-1. Much of the ETL is based on the data review and parameter study conducted by Woodson (1990); therefore, it is an effort to incorporate the results of recent data into a guidance document. In brief, the criteria given in the ETL are given in Table 1.1. The moderate damage level referred to in the table is described as that recommended for protection of personnel and sensitive equipment. Significant concrete scabbing and reinforcement rupture have not occurred at this level. The dust and debris environment on the protected side of the slab is moderate; however, the allowable slab motions are large. Heavy damage means that the slab is at incipient failure. Under this damage level, significant reinforcement rupture has occurred, and only concrete rubble remains suspended over much of the slab. The heavy damage level is recommended for cases in which heavy concrete scabbing can be tolerated, such as for the protection of water tanks and stored goods and other insensitive equipment.

14. Based on the data base, the ETL sets forth some design conditions that must be satisfied in order for one to use the response limits given in Table 1.1. The scaled range must exceed 0.5 $ft/lb^{1/3}$ and the span-to-effective-depth (L/d) ratio must exceed 5. Principal reinforcement spacing is to be minimized and shall never exceed the effective depth (d). Stirrup reinforcement is required, regardless of computed shear stress, to provide adequate concrete confinement and principal steel support in the large-deflection region. Stirrups are required along each principal bar at a maximum spacing of one-half the effective depth (d/2) when the scaled range is

less than 2.0 ft/lb$^{1/3}$ and at a maximum spacing equal to the effective depth at larger scaled ranges. When stirrups are also required to resist shear, the maximum allowable spacing is d/2. All stirrup reinforcement is to provide a minimum of 50 psi shear stress capacity. Some guidelines for ensuring adequate lateral restraint are also given in the ETL but will not be given here.

15. The following types of stirrups are permitted in the ETL:

a. Single-leg stirrups having a 135-degree bend at one end and at least a 90-degree bend at the other end. When 90-degree bends are used at one end, the 90-degree bend should be placed at the compression force.

b. U-shaped and multilegged stirrups with at least 135-degree bends at each end.

c. Closed-looped stirrups that enclose the principal reinforcement and have at least 135-degree bends at each end.

16. Criteria are given in the ETL to account for direct shear problems. It was observed from the data base that flexible slabs that are laterally restrained are much less likely to fail in direct shear because early in the response, lateral compression membrane forces will act to increase the shear capacity, and later in the response shear forces tend to be resolved into the principal reinforcement during tension membrane action. Tests indicate that direct shear failure can occur in slabs subjected to impulsive loads. It is generally known that shear failure is more likely to occur in reinforced concrete members with small L/d values than it is in those with large L/d values. Since the data base indicates that laterally restrained slabs with $L/d \geq 8$ are unlikely to experience direct shear failures, the ETL only requires design for direct shear for laterally restrained slabs having $L/d < 8$

and for all laterally unrestrained slabs. This is considered to be conservative, but the degree of conservatism is unknown due to gaps in the data base.

Objective

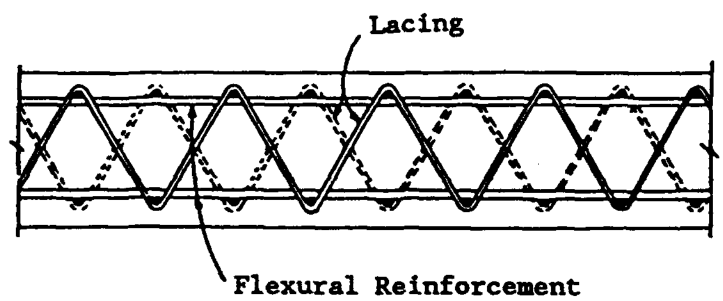
17. The overall objective was to gain a basic understanding of the role of shear reinforcement in enhancing the ductility of one-way reinforced concrete slabs. This includes a consideration of how shear reinforcement details interact with other physical details to affect the response limits of a slab. More specifically, the objective of this study was to develop and conduct an experimental investigation comparing the effects of stirrups and lacing bars on the large-deflection behavior of reinforced concrete slabs.

Scope

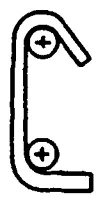
18. In the development of an experimental program, the study relied greatly on a recent data review and parameter study conducted by Woodson (1990). The design, execution, and evaluation of this experimental program primarily comprise the scope of this study.

Table 1.1. Design Criteria from ETL 1110-9-7

Lateral Restraint Condition	Damage Level	Response Limit (Support Rotation, Degrees)
Unrestrained	---	6
Restrained	Moderate	12
Restrained	Heavy	20



a. Lacing Reinforcement



b. Single-leg Stirrup

Figure 1.1. Shear Reinforcement

PART II: EXPERIMENTAL DESCRIPTION

General

19. Sixteen one-way reinforced concrete slabs were statically loaded at WES in May and June, 1991. The following sections describe the slabs' construction details, reaction structure details, instrumentation, experimental procedure, and material properties.

Construction Details

20. In addition to shear reinforcement details, the primary parameters that affect the large-deflection behavior of a one-way reinforced concrete slab include: support conditions, amount and spacing of principal reinforcement, scaled range (for blast loads), and span-to-effective-depth (L/d) ratios. The effects of these parameters on the structural response of a slab must be considered in the study of the role of shear reinforcement.

21. The slabs were designed to reflect the interaction of shear reinforcement details with the other primary parameters. Table 2.1 qualitatively presents the characteristics of each slab. Table 2.2 presents the same characteristics in a quantitative manner, reflecting the practical designs based on available construction materials. All slabs were designed to be loaded in a clamped (laterally and rotationally restrained) condition and may be considered to be approximately 1/4-scale models of prototype wall or roof slabs of protective structures. Each slab had a clear span of 24 inches, a width of 24 inches, and an effective depth of 2.4 inches, maintaining the L/d ratio at a value of 10. In general, the experimental program was designed to compare the effects of lacing bars and stirrups on slab behavior for three different values of principal reinforcement and three values of shear reinforcement spacing.

22. D1, D2, and D3 deformed wires (heat-treated in the laboratory) were used for reinforcement. It was important that the ratio of principal steel spacing to slab effective depth be generally maintained. Data indicated that this ratio should be less than 1.0. This ratio was maintained at a value of approximately 0.6. The shear reinforcement spacing was varied from a value equal to the effective depth (d) to approximately 3d/4 and d/2 (d/2 is typically the value given in design manuals for blast-resistant structures). It was impossible to maintain all of these parameters exactly using the reinforcement bar sizes available, but the variations are slight. For example, the shear reinforcement ratio category is "medium" for both slab no. 6 and slab no. 7. The actual values are 0.0034 and 0.0036 for slab nos. 6 and 7, respectively. The values of shear reinforcement ratio are identical when compared between a laced slab and a slab with stirrups for any category. Figure 2.1 is a plan view showing typical slab proportions and the principal steel and temperature steel layouts for one of the slabs (slab no 9). The reinforcement patterns for the other slabs were similar, differing by the principal steel details given in Table 2.2.

23. The temperature steel spacing was identical for all of the slabs, but one difference in the temperature steel placement occurred between laced and unlaced slabs. The temperature steel was placed exterior to the principal steel in the laced slabs, but it was placed interior to the principal steel in the slabs having stirrups or no shear reinforcement. One exception was slab no.13 (contained stirrups) in which the temperature steel was placed exterior to principal steel to allow an evaluation of the effects of this parameter on slab behavior.

24. Figures 2.2, 2.3, and 2.4 are sectional views cut through the lengths of the laced slabs. The dashed lacing bar in each figure indicates the configuration of the lacing bar associated with the next principal steel bar. In other words, the positions of the lacing bars alternated to encompass all temperature steel bars. However, some temperature steel bars were not confined in slab nos. 4 and 5. Figure 2.5 shows typical stirrup details for slabs with D3 principal reinforcement. The stirrups for slabs with D1 principal steel were similar, differing only in length due to the differences in principal steel bar diameter. In slabs with stirrups, the stirrups were spaced along the principal steel bar at the spacings shown in Table 2.2.

25. The slabs were constructed in the laboratory with much care to ensure quality construction with minimal error in reinforcement placement. Figures 2.6 and 2.7 are photographs of slab nos. 7 and 12 prior to the placement of concrete. Figure 2.8 is a close-up view of the lacing in slab no. 7.

Reaction Structure Details

26. Figure 2.9 shows a cross-sectional view of the reaction structure. The reaction structure had a removable door to allow access to the volume beneath the slab specimen. Placement of a 36- by 24-inch slab in the reaction structure allowed 6 inches of the slab at each end to be clamped by a steel plate bolted into position, thereby leaving a 24- by 24-inch one-way restrained slab for the experiment.

Instrumentation

27. Each slab was instrumented for strain, displacement, and pressure measurement. The data were digitally recorded with a personal computer. Two displacement transducers were used in each experiment to measure vertical displacement of the slab, one at one-quarter span and one at midspan. The displacement transducers used were Celesco Model PT-101, having a working range of 10 inches. Two single-axis, metal film, 0.125-inch-long, 350-ohm, strain gage pairs were installed on principal reinforcement in each slab. Each pair consisted of a strain gage on a top bar and one on a bottom bar directly below. One pair was located at one-quarter span (ST-1, SB-1), and one was located at midspan (ST-2, SB-2).

28. Strain gages were also installed at midheight on shear steel in slabs having such reinforcement. In as much as possible, strain gages were placed on lacing bars in laced slabs at locations similar to locations of gages on stirrups in slabs with stirrups. The gages were placed on the shear reinforcement associated with the middle principal steel bar. In slabs with stirrups, the locations of stirrups with strain gages were as follows:

Slab no. 10:

- Strain gages on four stirrups.
- One each on stirrups located at 6.0, 8.4, 13.2, and 18.0 inches from end of 24- by 36-inch slab; SL-1, SL-2, SL-3, and SL-4, respectively.

Slab no. 11:

- Strain gages on four stirrups.
- One each on stirrups located at 6.0, 7.85, 11.55, and 17.10 inches from end of 24- by 36-inch slab; SL-1, SL-2, SL-3, and SL-4, respectively.

Slab no. 12:

- Strain gages on four stirrups.
- One each on stirrups located at 6.0, 7.85, 11.55, and 17.10 inches from

end of the 24- by 36-inch slab; SL-1, SL-2, SL-4, respectively.

Slab no. 13:

- Strain gages on four stirrups.
- One each on stirrups located at 6.0, 7.85, 11.55, and 17.10 inches from end of the 24- by 36-slab; SL-1, SL-2, SL-3, and SL-4, respectively.

Slab no. 14:

- Strain gages on four stirrups.
- One each on stirrups located at 6.0, 7.2, 12.0, and 18.0 inches from end of the 24- by 36-inch slab; SL-1, SL-2, SL-3, and SL-4, respectively.

Slab no. 15:

- Strain gages on four stirrups.
- One each on stirrups located at 6.0, 7.2, 12.0, and 18.0 inches from end of the 24- by 36-inch slab; SL-1, SL-2, SL-3, and SL-4, respectively.

Slab no. 16:

- Strain gages on four stirrups.
- One each on stirrups located at 6.0, 7.2, 12.0, and 18.0 inches from end of the 24- by 36-inch slab; SL-1, SL-2, SL-3, SL-4, respectively.

Figures 2.10, 2.11, and 2.12 show the locations of the strain gages on the shear reinforcement in the laced slabs. Two Kulite Model HKM-S375, 500-psi-range pressure gages (P1 and P2) were mounted in the bonnet of the test chamber in order to measure the water pressure applied to the slab.

Experimental Procedure

29. The 4-foot diameter blast load generator (Figure 2.13) was used to statically load the slabs with water pressure. The reaction structure was placed inside the test chamber and surrounded with compacted sand. The slab was then placed on the reaction structure. The wire leads from the instrumentation gages and transducers were connected. After placing the removable door in position, the sand backfill was completed on the door side. A 1/4-inch-thick fiber-reinforced neoprene rubber membrane was placed over the

slab, and 1/2- by 24-inch steel plates were bolted into position as shown in Figure 2.14. Prior to the bolting of the plates, a waterproofing putty was placed between the rubber membrane and the steel plates to seal gaps around the bolts and to prevent loss of water pressure during the experiment. A torque wrench was used to achieve approximately 50 foot-pounds on each bolt, and a consistent sequence of tightening the bolts was use for each slab. The bonnet was bolted into position with forty 1-1/8-inch-diameter bolts tightened with a pneumatic wrench. A commercial waterline was diverted to the chamber's bonnet. The data recorder (personal computer) was started immediately preceding the opening of the waterline valve. A time of approximately 18 minutes was required to fill the bonnet volume of the chamber. A relief plug in the top of the bonnet indicated when the bonnet had been filled. At that time, the waterline valve was closed to allow closing of the relief plug. The waterline valve was again opened slowly, allowing a flow of approximately 1.0 gal/min through the 1/4-inch-diameter waterline and inducing a slowly increasing load to the slab's surface. A pneumatic water pump was connected to the waterline to facilitate water pressure loading in the case that commercial line pressure was not great enough to reach ultimate resistance of the slab in any particular experiment. Monitoring of the pressure gages and deflection gages indicated the behavior of the slab during the experiment and enabled the engineer to make a decision for termination by closing the waterline valve. Following termination of the experiment, the bonnet was drained and remove. Detailed measurements and photographs of the slab were taken after removal of the neoprene membrane. Finally, the damaged slab was removed and the reaction structure was prepared for another slab.

Table 2.1. Slab Characteristics (Qualitative)

Slab	$\rho_{tension}$	ρ_{shear}	Lacing	Stirrups	Principal Steel Spacing	Shear Steel Spacing
1	small	none	-	-	0.67d	-
2	medium	none	-	-	0.63d	-
3	large	none	-	-	0.55d	-
4	small	small	x		0.67d	d
5	large	small	x		0.55d	d
6	small	medium	x		0.67d	3d/4
7	medium	medium	x		0.63d	3d/4
8	small	large	x		0.67d	d/2
9	large	large	x		0.55d	d/2
10	small	small		x	0.67d	d
11	small	medium		x	0.67d	3d/4
12	medium	medium		x	0.63d	3d/4
13 (Temperature steel placed exterior to principal steel)	medium	medium		x	0.63d	3d/4
14	small	large		x	0.67d	d/2
15	large	small		x	0.55d	d
16	large	large		x	0.55d	d/2

Table 2.2. Slab Characteristics (Quantitative)

Slab	$\rho_{tension}$	ρ_{shear}	Lacing	Stirrups	Principal Steel Spacing	Shear Steel Spacing
1	0.0025	none	-	-	D1 @ 1.60"	-
2	0.0056	none	-	-	D2 @ 1.50"	-
3	0.0097	none	-	-	D3 @ 1.33"	-
4	0.0025	0.0026	x		D1 @ 1.60"	2.4"
5	0.0097	0.0031	x		D3 @ 1.33"	2.4"
6	0.0025	0.0034	x		D1 @ 1.60"	1.85"
7	0.0056	0.0036	x		D2 @ 1.50"	1.85"
8	0.0025	0.0052	x		D1 @ 1.60"	1.2"
9	0.0097	0.0063	x		D3 @ 1.33"	1.2"
10	0.0025	0.0026		x	D1 @ 1.60"	2.4"
11	0.0025	0.0034		x	D1 @ 1.60"	1.85"
12	0.0056	0.0036		x	D2 @ 1.50"	1.85"
13 (Temperature steel placed exterior to principal steel)	0.0056	0.0036		x	D2 @ 1.50"	1.85"
14	0.0025	0.0052		x	D1 @ 1.60"	1.2"
15	0.0097	0.0031		x	D3 @ 1.33"	2.4"
16	0.0097	0.0063		x	D3 @ 1.33"	1.2"

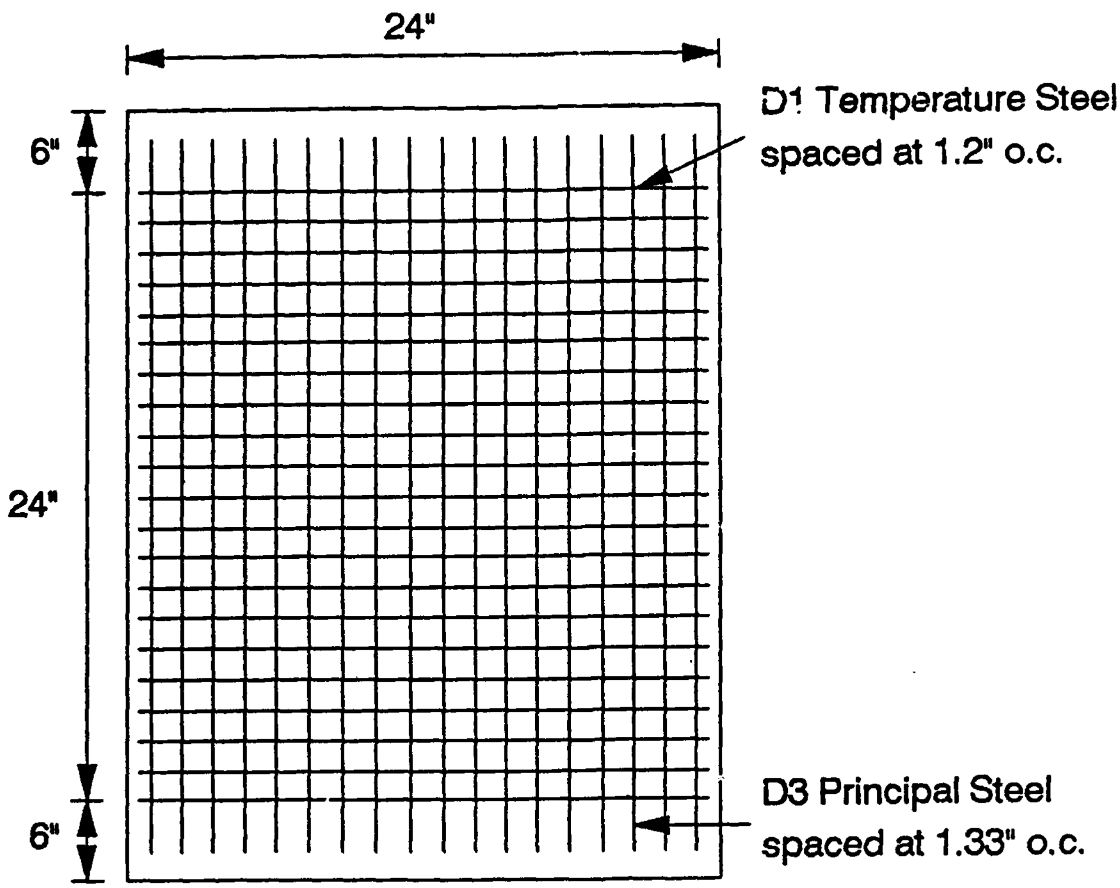


Figure 2.1. Reinforcement Layout for Slab No. 9

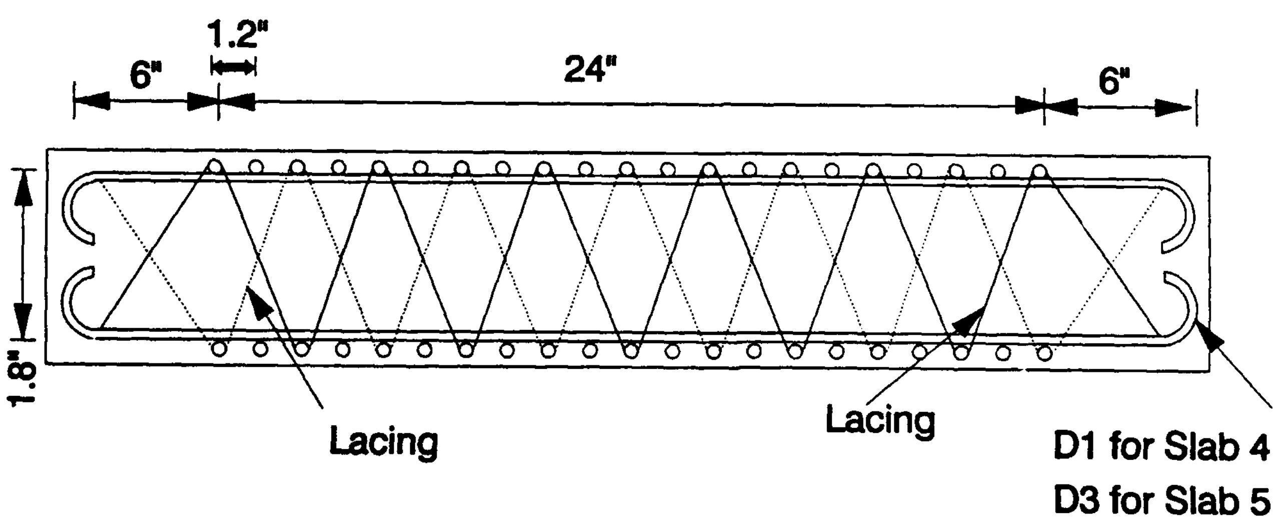


Figure 2.2. Sectional View Through Length of Slab Nos. 4 and 5

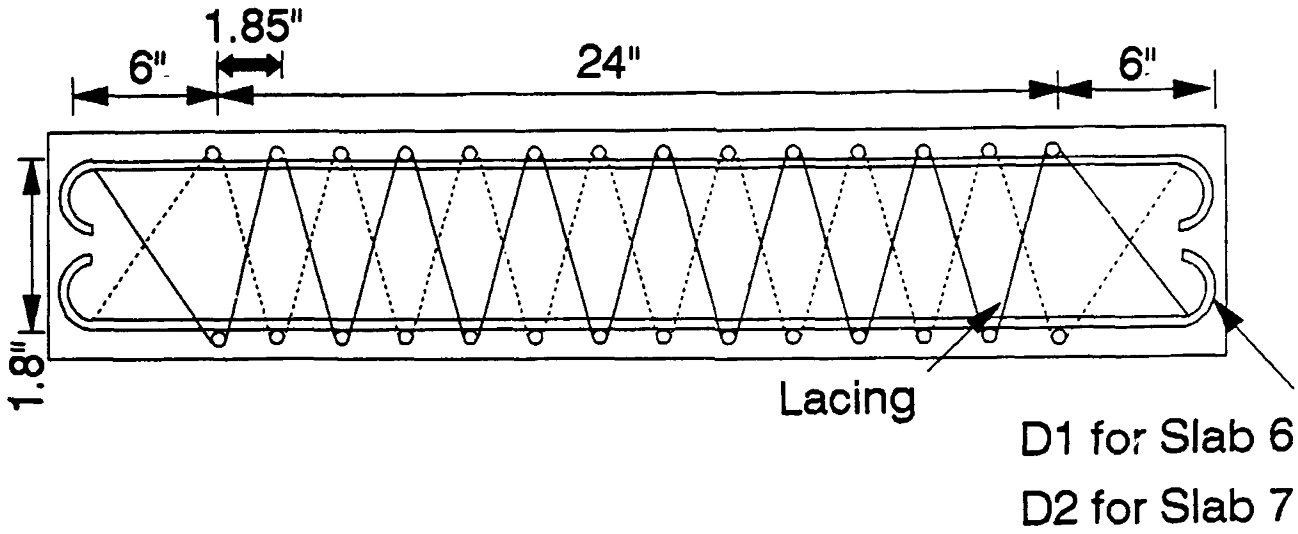


Figure 2.3. Sectional View Through Length of Slab Nos. 6 and 7

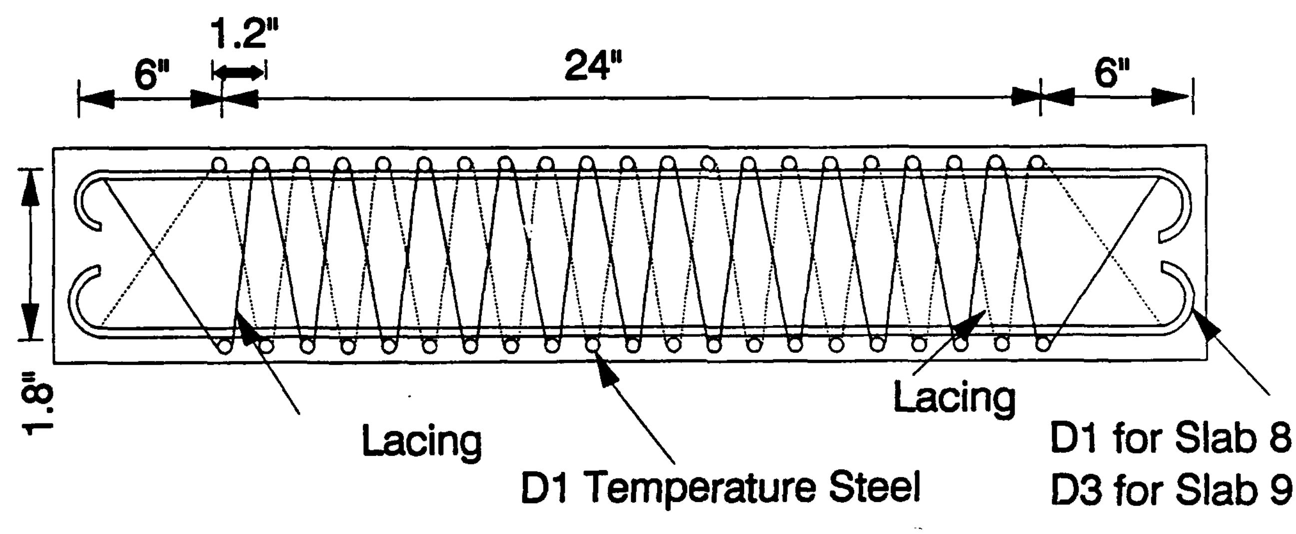


Figure 2.4. Sectional View Through Length of Slab Nos. 8 and 9

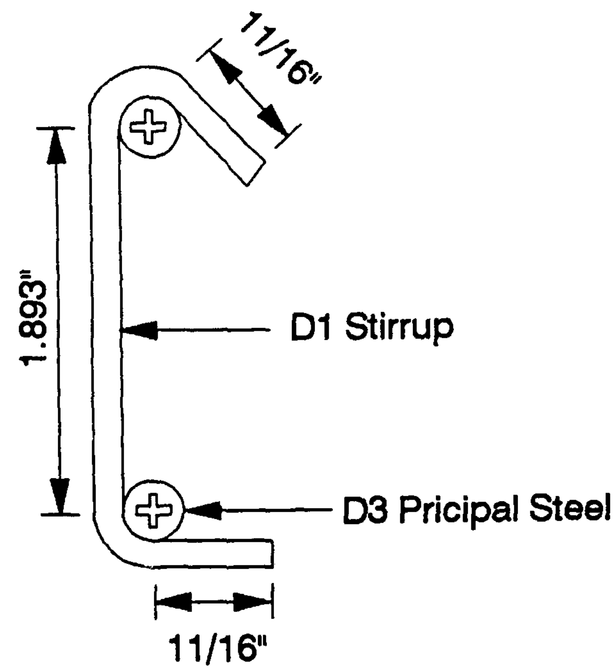


Figure 2.5. Stirrup Details for Slabs with D3 Principal Steel

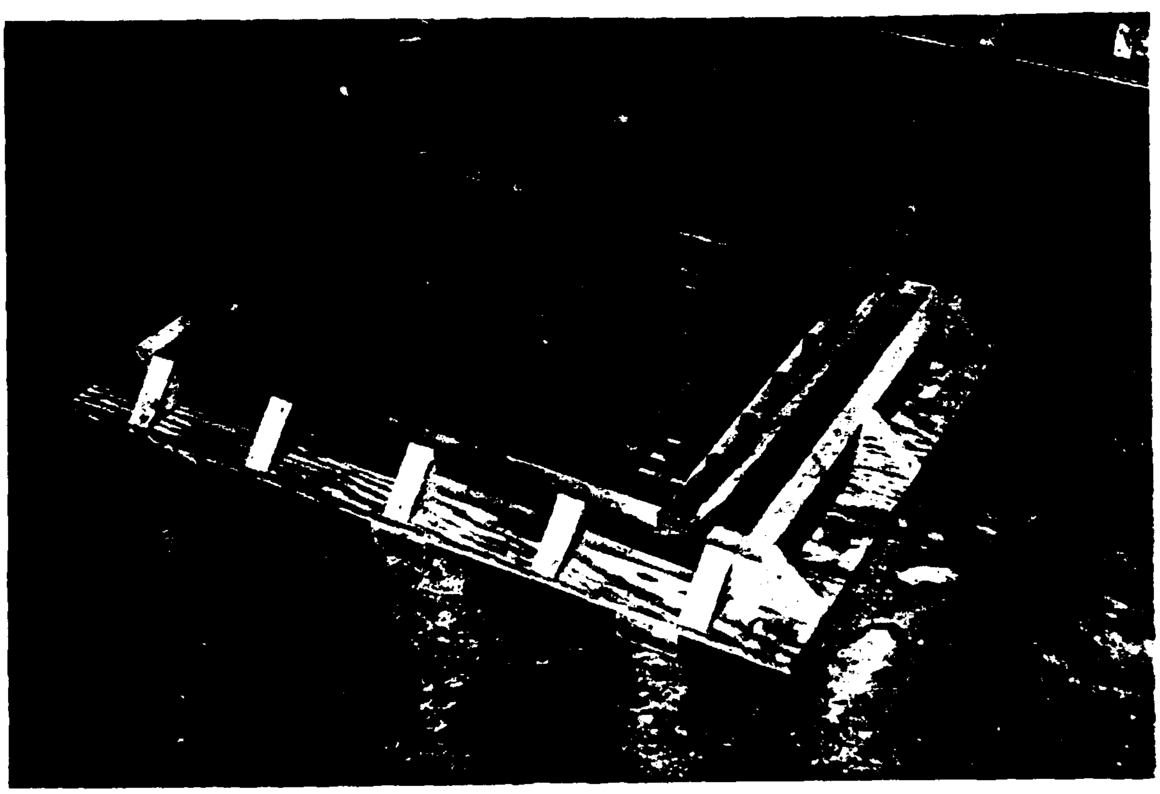


Figure 2.6. Slab No. 7 Prior to Concrete Placement

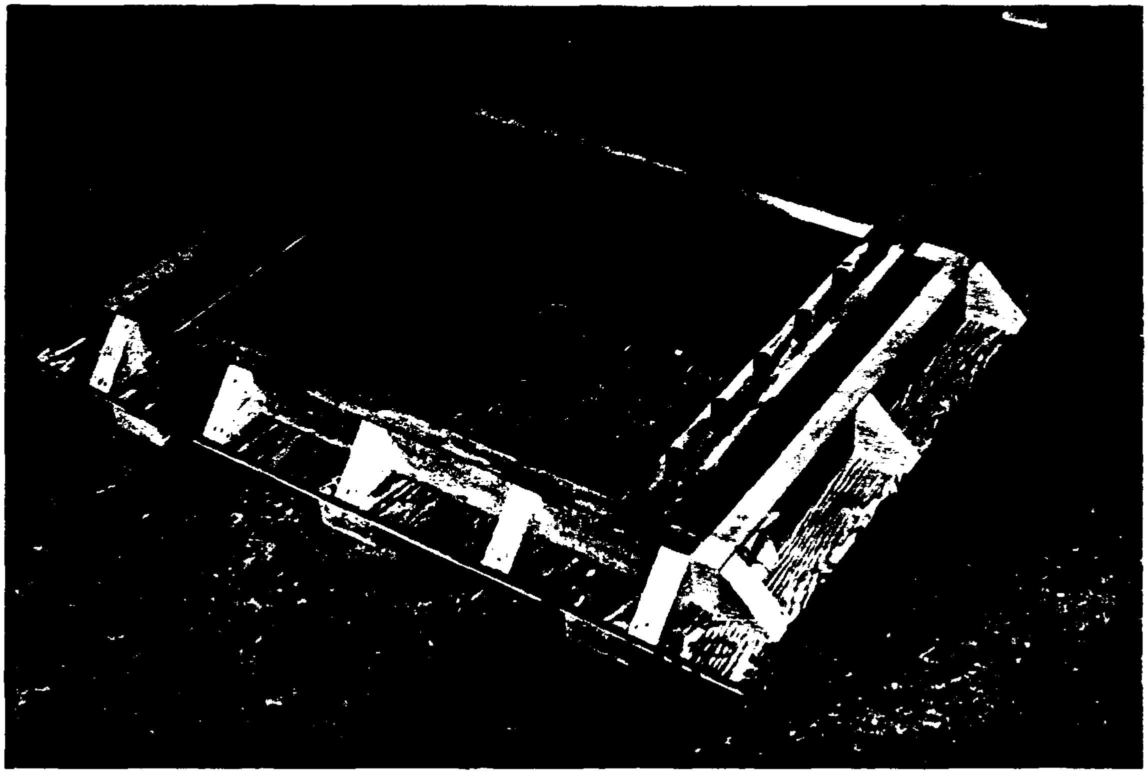


Figure 2.7. Slab No. 12 Prior to Concrete Placement

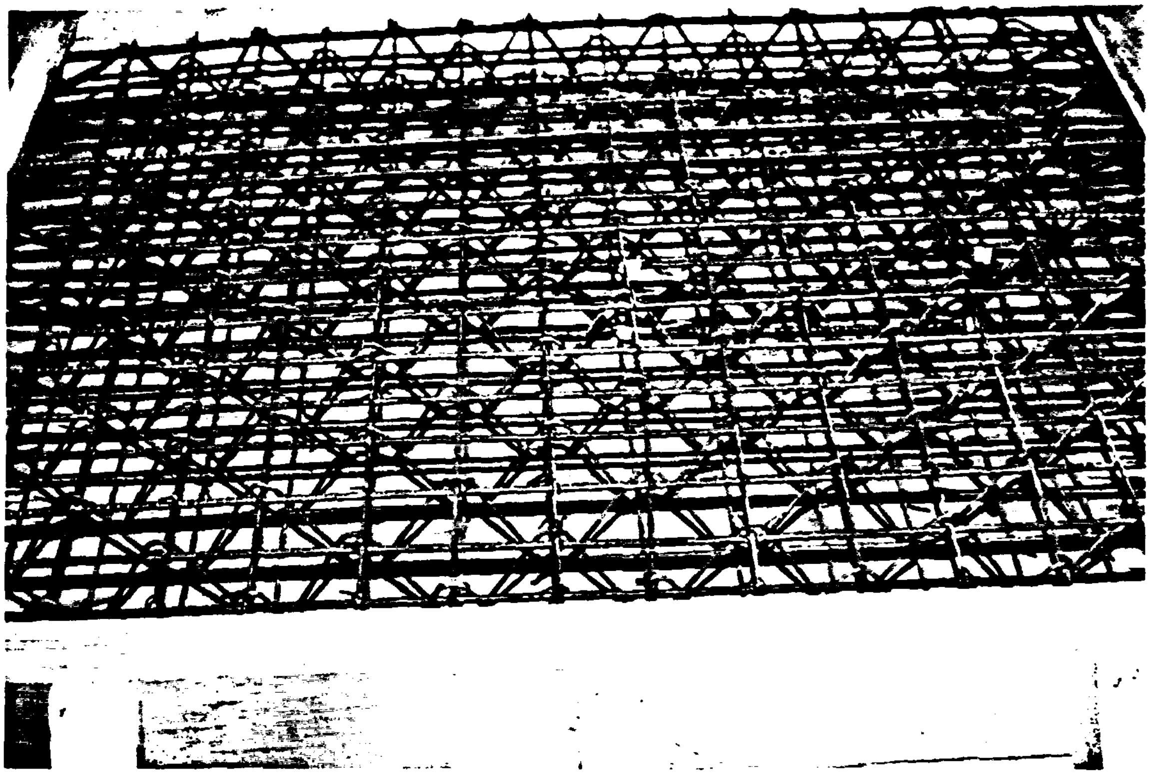


Figure 2.8. Lacing in Slab No. 7

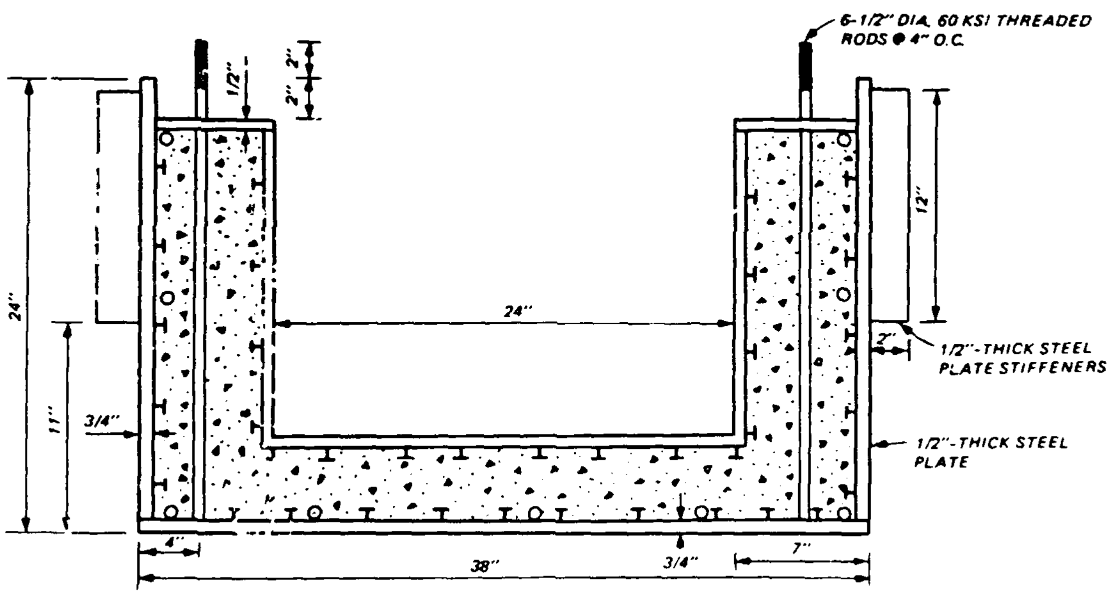


Figure 2.9 . Reaction Structure

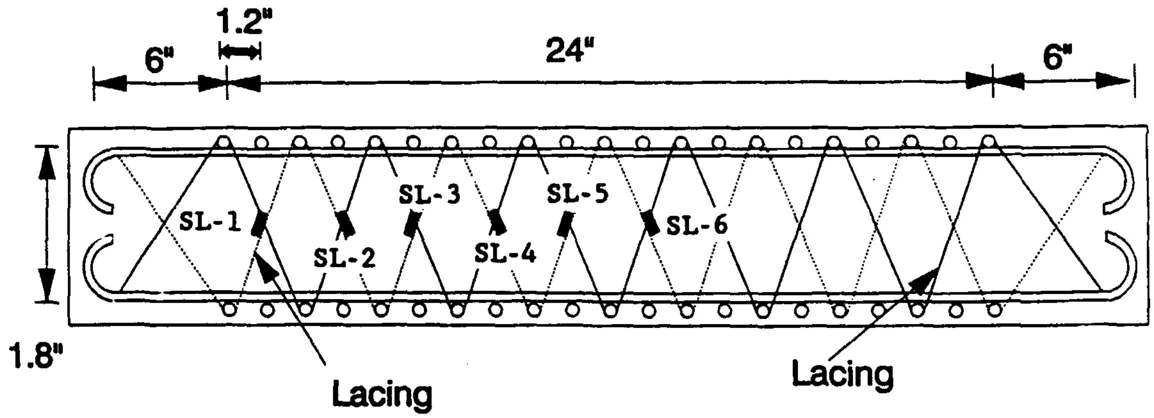


Figure 2.10. Strain Gage Locations on Lacing in Slab Nos. 4 and 5

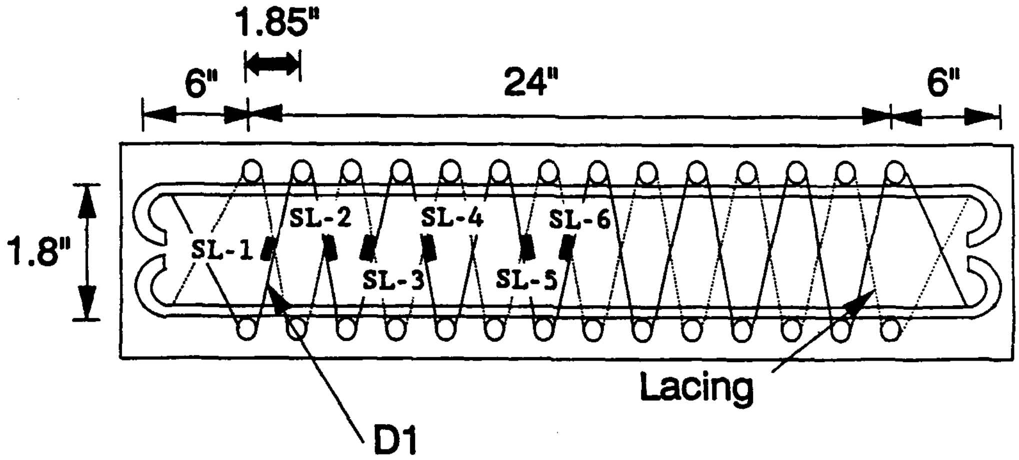


Figure 2.11. Strain Gage Locations on Lacing in Slab Nos. 6 and 7

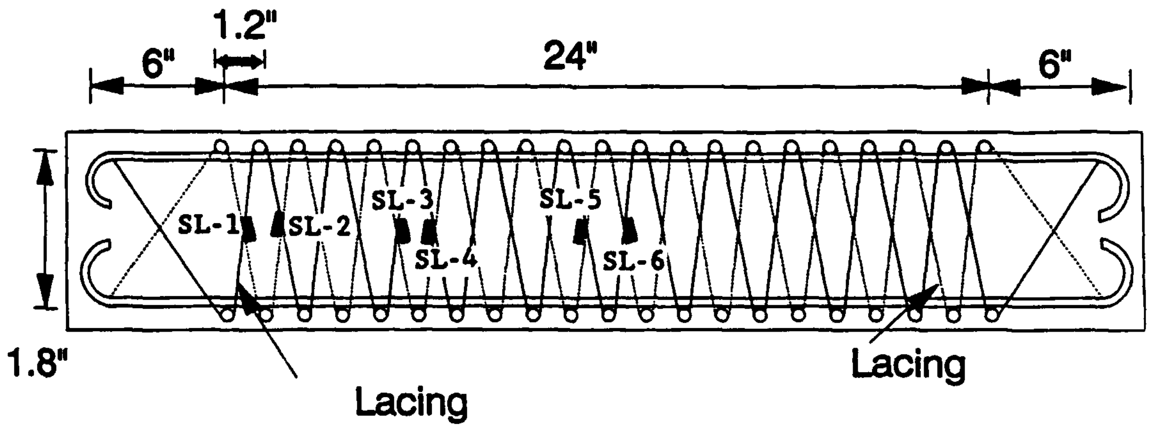


Figure 2.12. Strain Gage Locations on Lacing in Slab Nos. 8 and 9

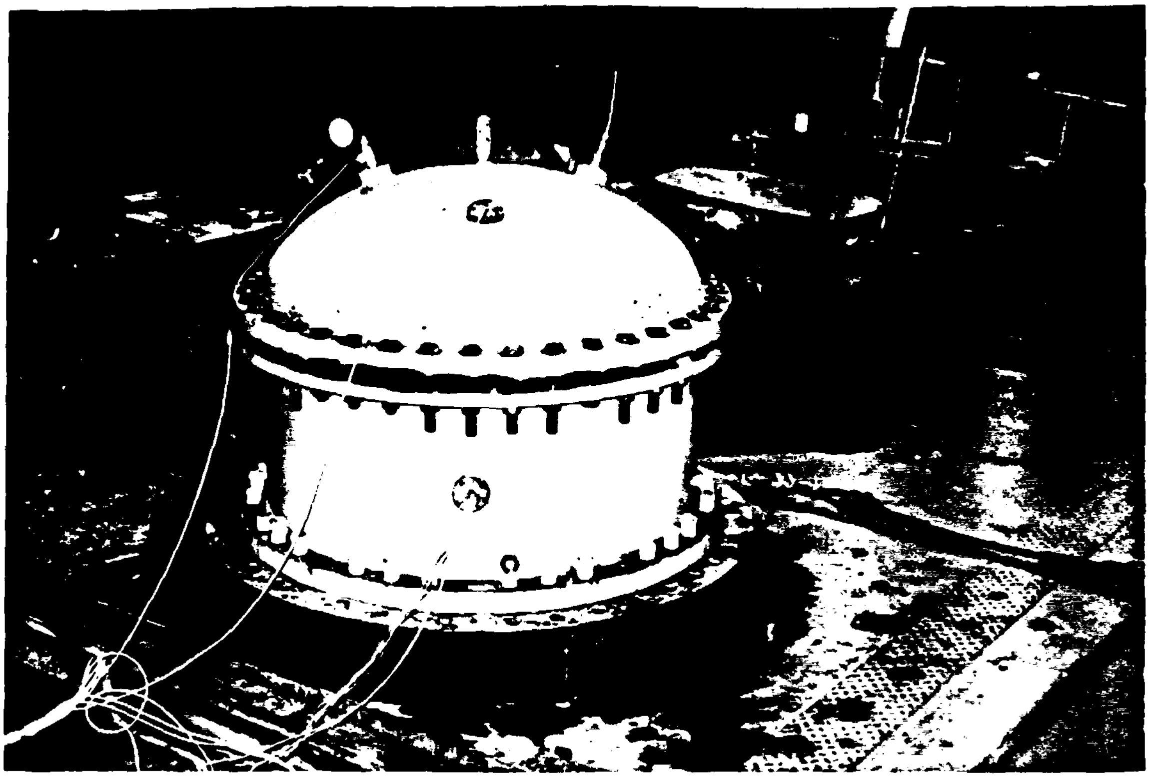


Figure 2.13. Four-foot-diameter Blast Load Generator

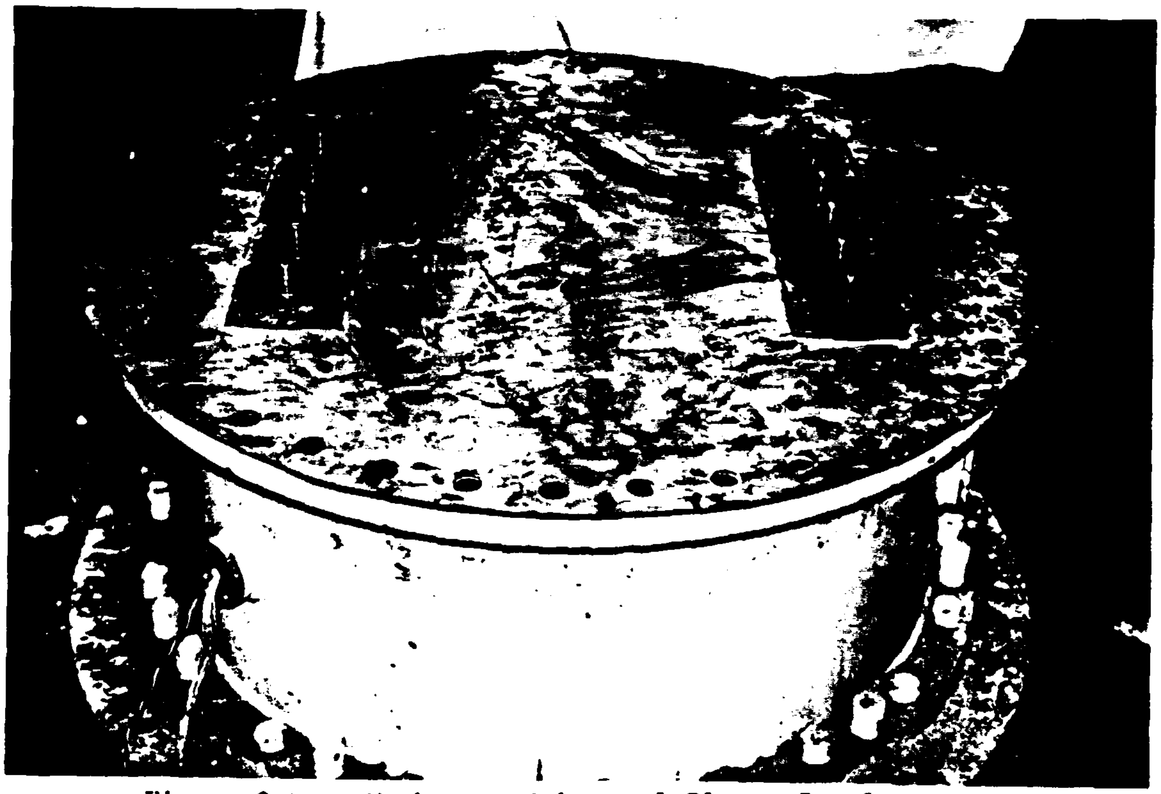


Figure 2.14. Membrane with Steel Plates In-place

PART III: EXPERIMENTAL RESULTS

Structural Damage

30. Detailed posttest measurements and inspection provided a data check and damage assessment of each slab prior to removal from the reaction structure. Figures 3.1 through 3.16 show the posttest condition of each slab immediately after removal of the neoprene membrane. Figure 3.17 is a side view schematic of the general three-hinge mechanism that was found in each slab. The values of measured posttest midspan deflection, for each slab are presented in Table 3.1.

31. Figure 3.18 is a posttest view of the undersurfaces ratio of all sixteen slabs. The slabs are numbered in increasing order from left to right with slab nos. 1 through 5 being shown on the front row.

32. The approximate widths of the cracks and regions of crushed concrete are presented in Table 3.2. The left support is taken to be that on one's left-hand side when looking at the slab from the side with the reaction structure's removable door (the view shown in Figure 3.1 through 3.16).

33. A detailed survey of the damage over the entire top and bottom surfaces of the slabs resulted in Figures 3.19 through 3.34. These figures indicate light, medium, and heavy damage. The structural damage is discussed in Part IV of this report.

Instrumentation Data

34. The electronically recorded data are presented in Appendix A. All of the strain gage readings and the deflection gage readings were plotted against the readings of both of the pressure transducers (P-1 and P-2) readings for each experiment. For the plots presented in Appendix A, the strain and deflection

measurements versus only one of the pressure gage's readings are shown.

35. In general, the quality of the recovered data was good. As often occurs when many strain gages at embedded in concrete, several strain gages did not function properly. These included: SL-4 in slab no. 8; SL-1 and SL-6 in slab no. 9; SL-1, SL-5, and SL-6 in slab no. 10; ST-1, SL-5, and SL-6 in slab no. 11; SL-6 in slab no. 12; SL-5 and SL-6 in slab no. 13; SL-3, SL-5, and SL-6 in slab no. 14; SL-6 in slab no. 15; and SL-6 in slab no. 16. All but one of these malfunctioning gages were located on shear reinforcement. One was located on a top principal reinforcement bar.

Table 3.1. Posttest Measured Midspan Deflection

Slab No.	Δ (inches)
1	4.4
2	1.5
3	*
4	5.5
5	7.0
6	5.5
7	4.5
	5.5
9	5.3
10	5.0
11	5.9
12	5.7
13	7.0
14	5.7
15	5.3
16	5.1

* Slab no. 3 failed in shear near the support.

Table 3.2. Crack Widths

Slab	Top Crack Left Support (inches)	Bottom Crack Midspan (inches)	Top Crack or Crushed Area, Midspan (inches)	Top Crack Right Support (inches)
1	1.38	1.88	1.5	1.13
2	0.25	NA	NA	NA
3	4.0	NA	NA	NA
4	1.13	2.5	2.5	1.13
5	3.0	6.75	5.0	3.0
6	1.25	3.5	2.5	1.5
7	0.88	2.13	2.5	0.88
8	1.5	3.13	2.5	1.25
9	3.0	2.25	2.0	1.25
10	1.0	2.13	2.5	1.25
11	1.25	3.38	3.25	1.5
12	2.0	4.0	4.5	1.75
13	3.0	6.75	5.0	3.0
14	1.25	3.25	2.0	1.25
15	1.25	2.25	5.5	2.0
16	1.25	2.75	2.0	1.25

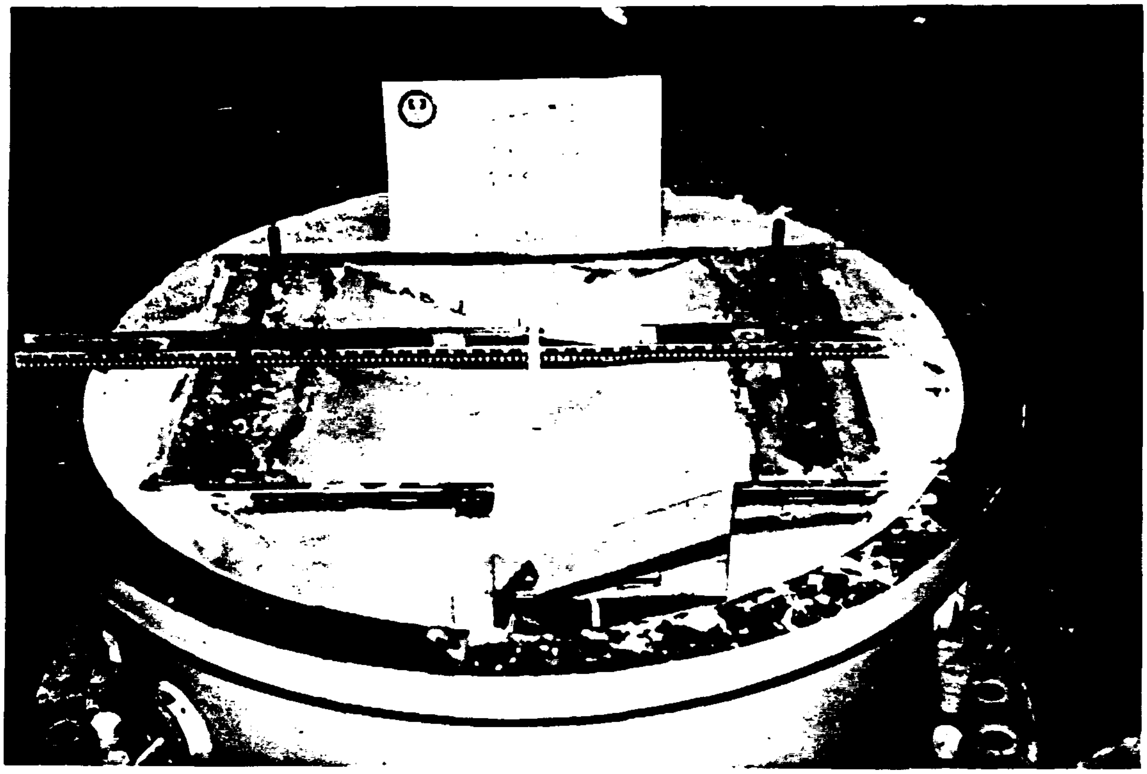


Figure 3.1. Posttest View of Slab No. 1

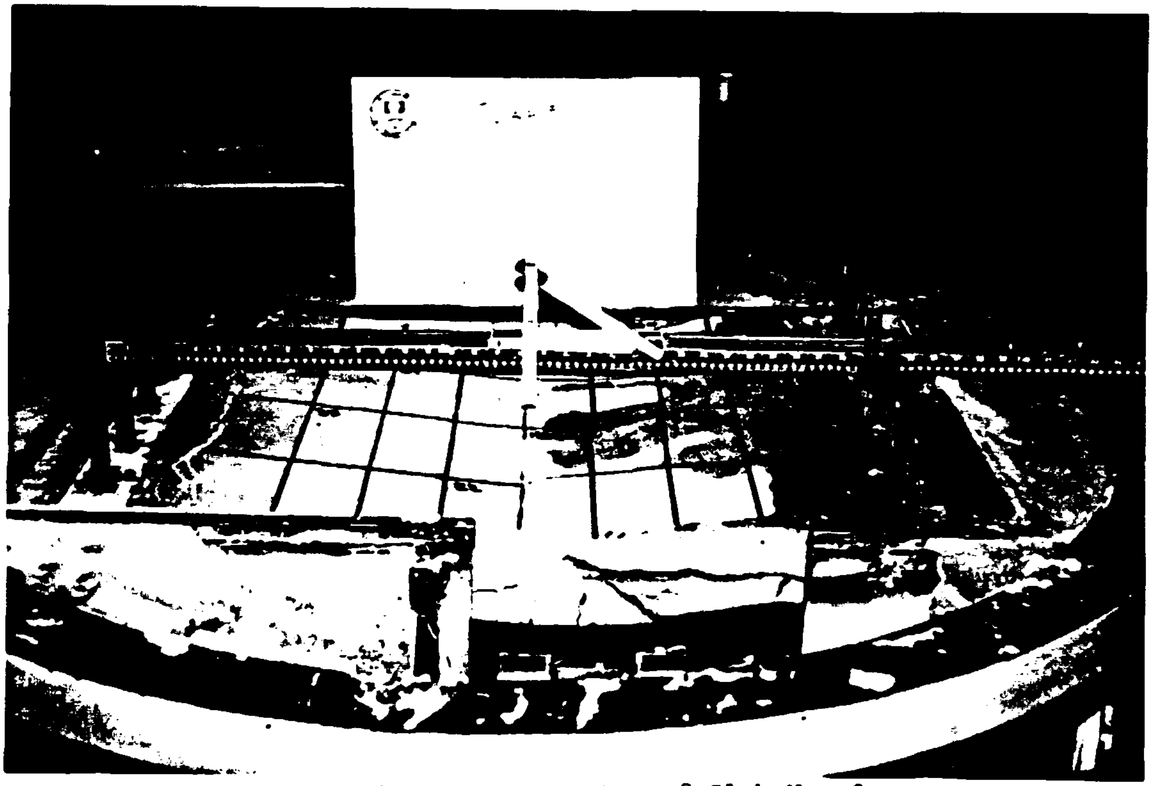


Figure 3.2. Posttest View of Slab No. 2

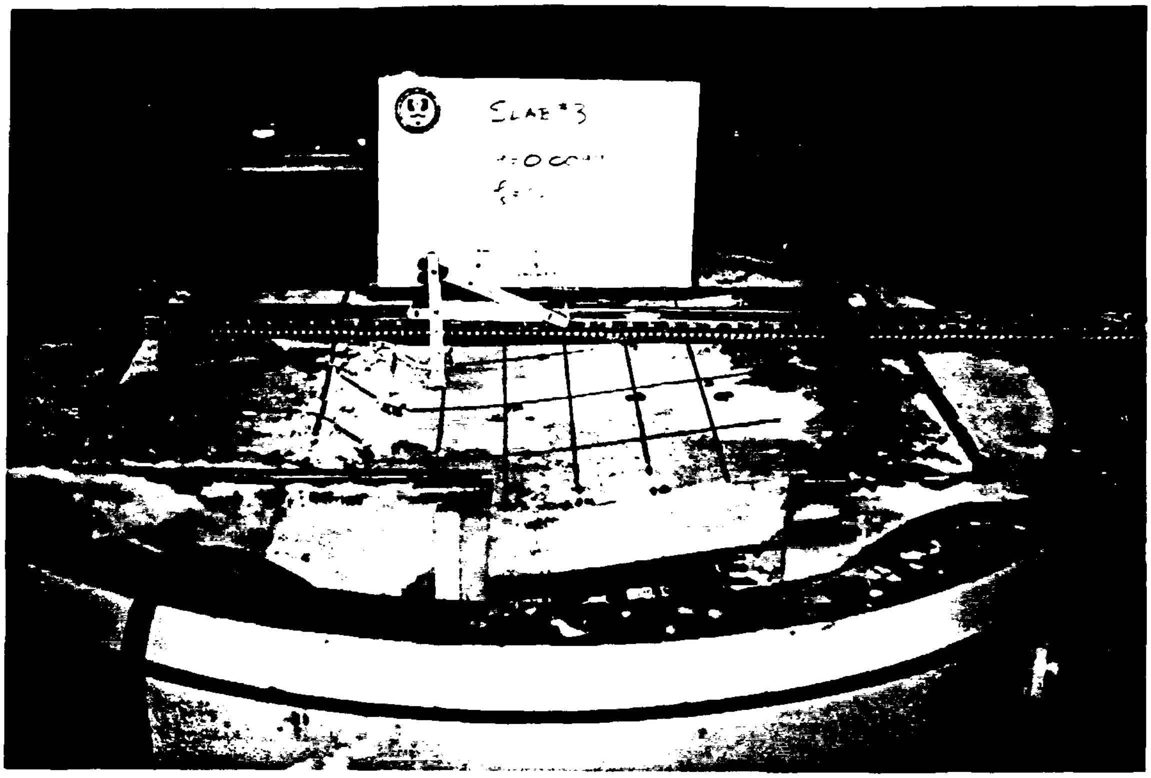


Figure 3.3. Posttest View of Slab No. 3

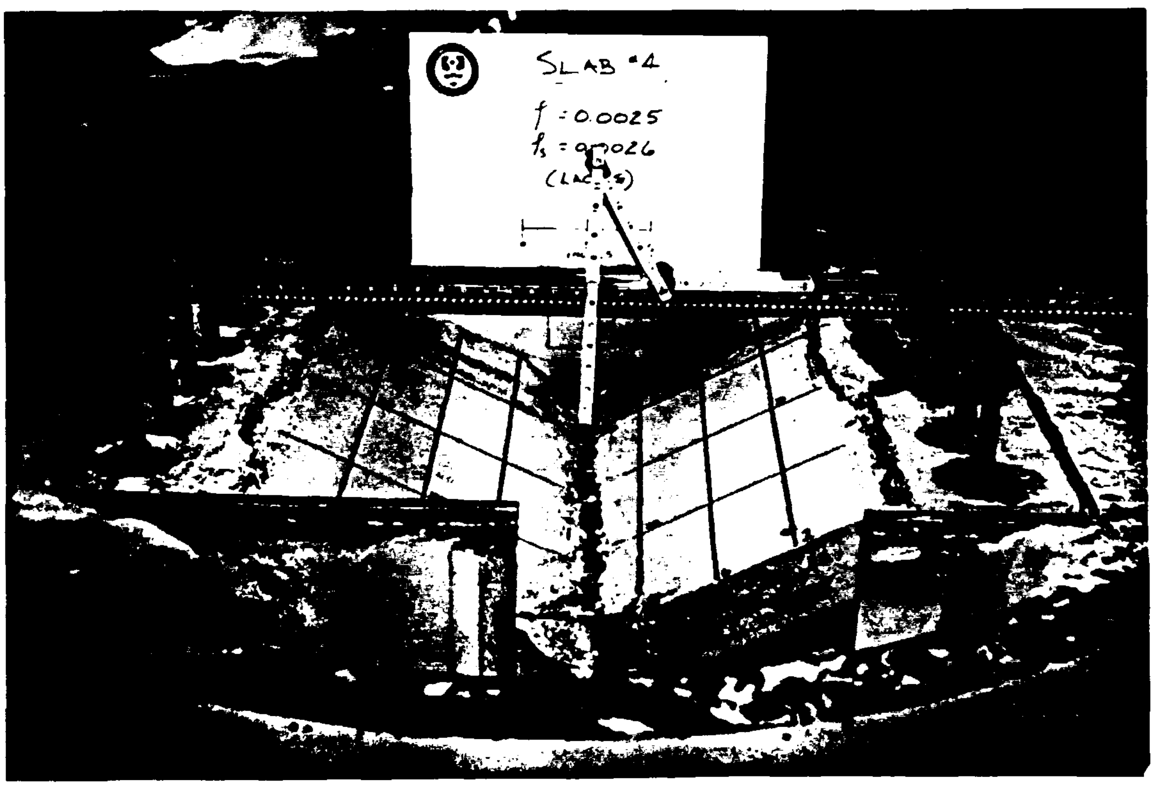


Figure 3.4. Posttest View of Slab No. 4

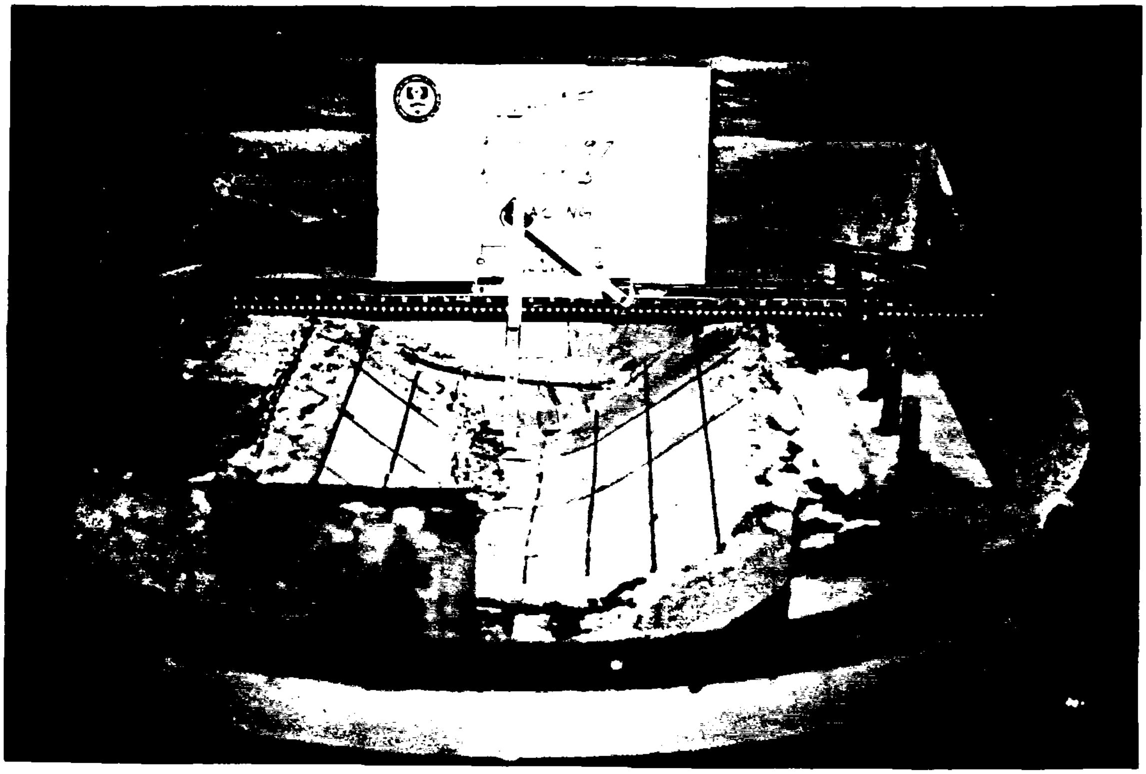


Figure 3.5. Posttest View of Slab No. 5

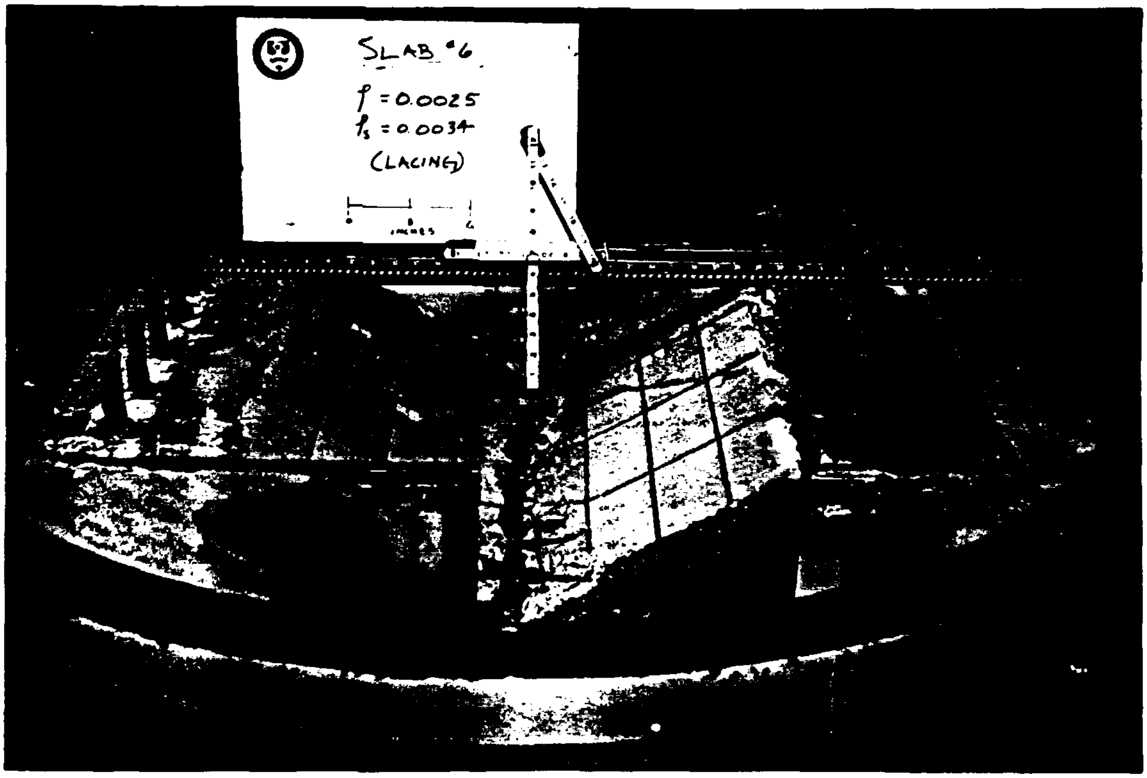


Figure 3.6. Posttest View of Slab No. 6

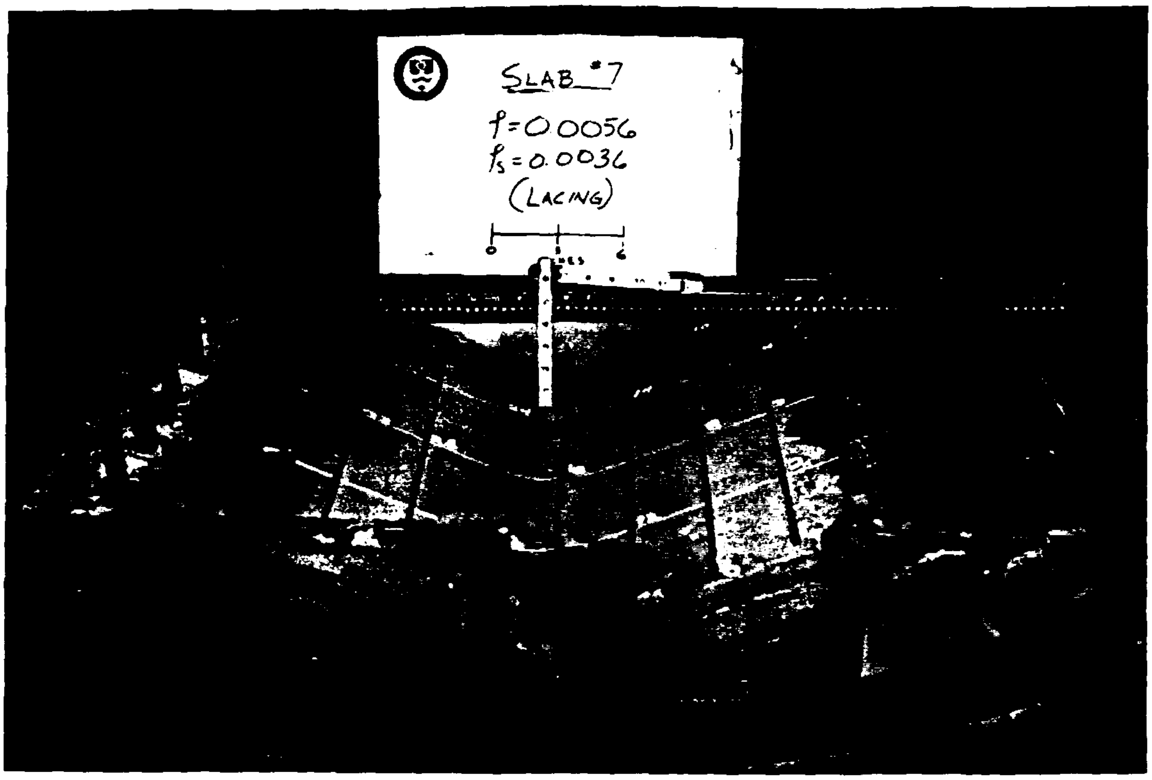


Figure 3.7. Posttest View of Slab No. 7

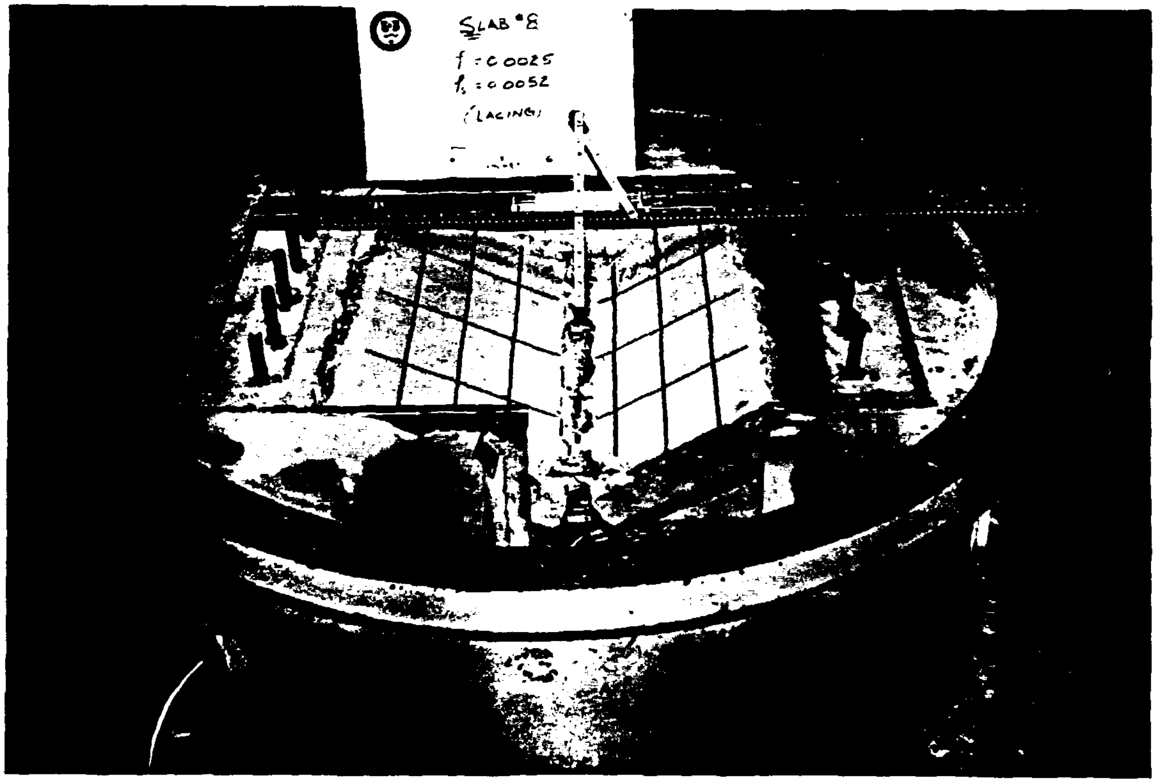


Figure 3.8. Posttest View of Slab No. 8

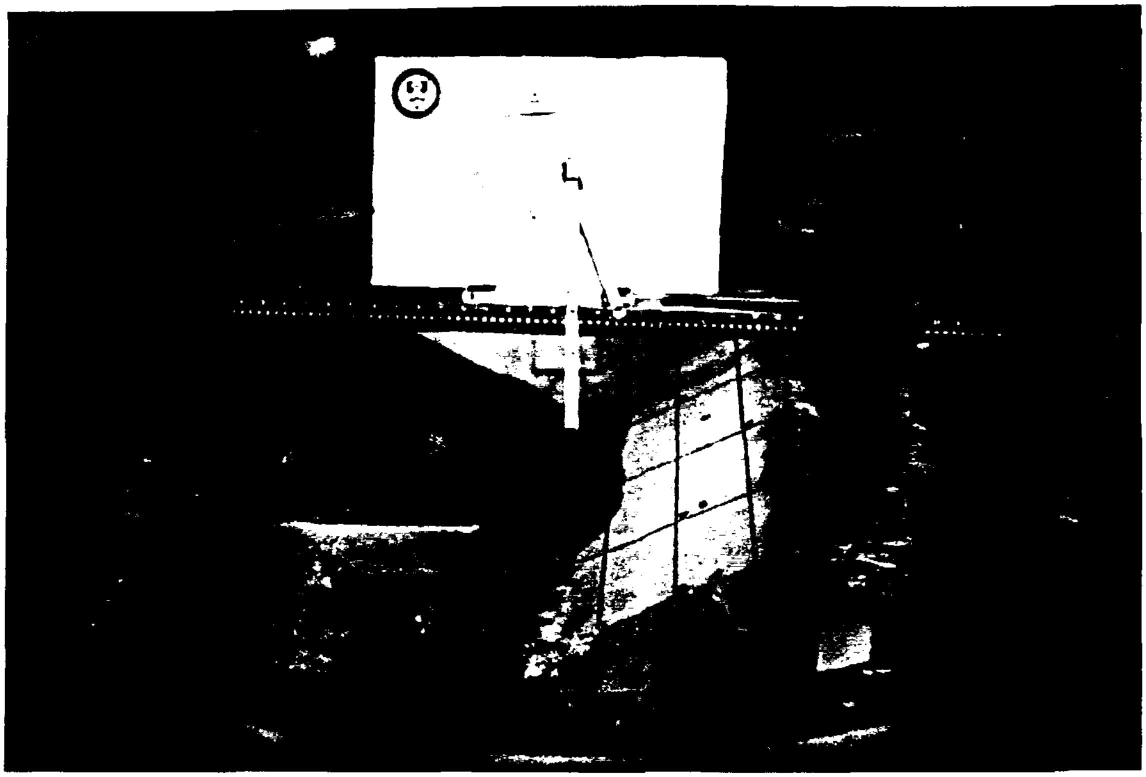


Figure 3.9. Posttest View of Slab No. 9

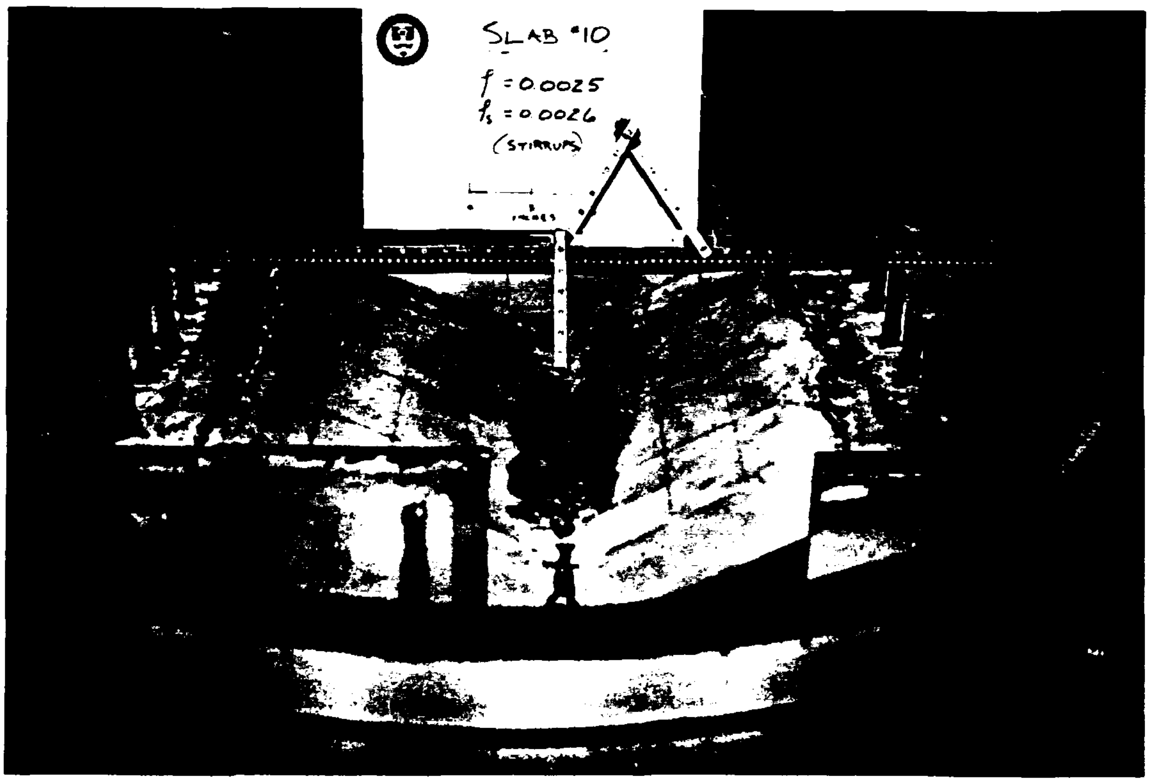


Figure 3.10. Posttest View of Slab No. 10

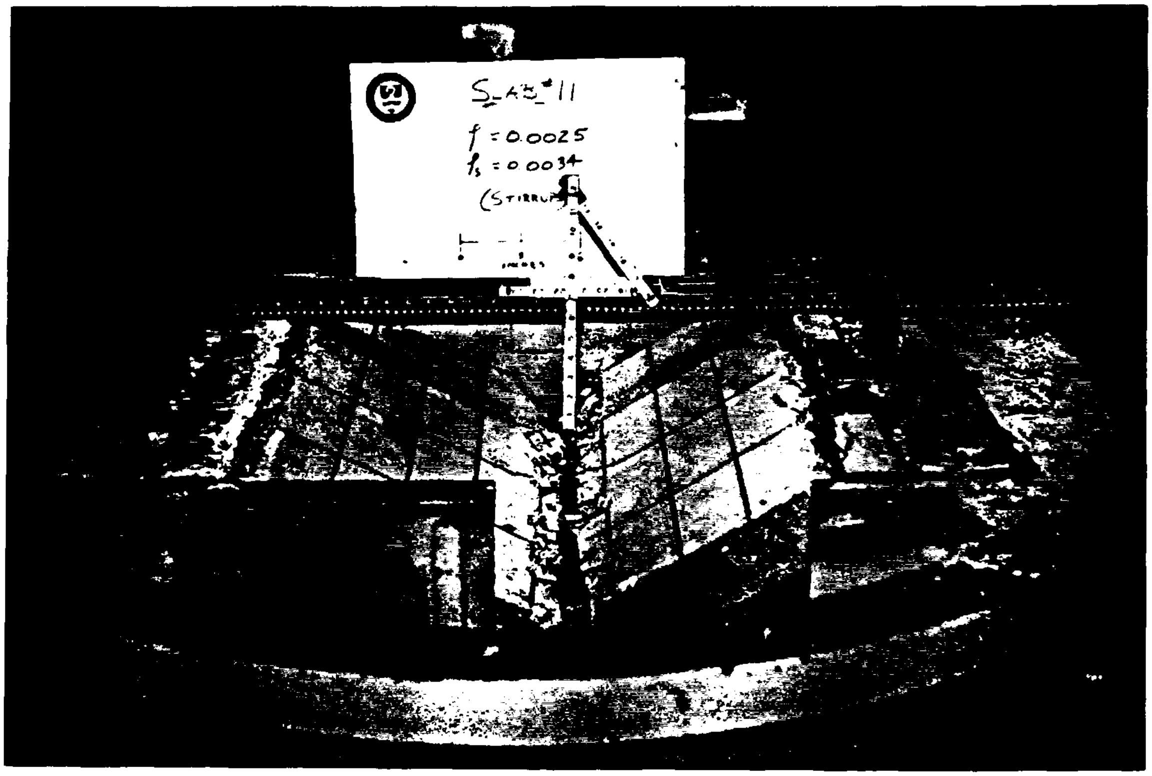


Figure 3.11. Posttest View of Slab No. 11

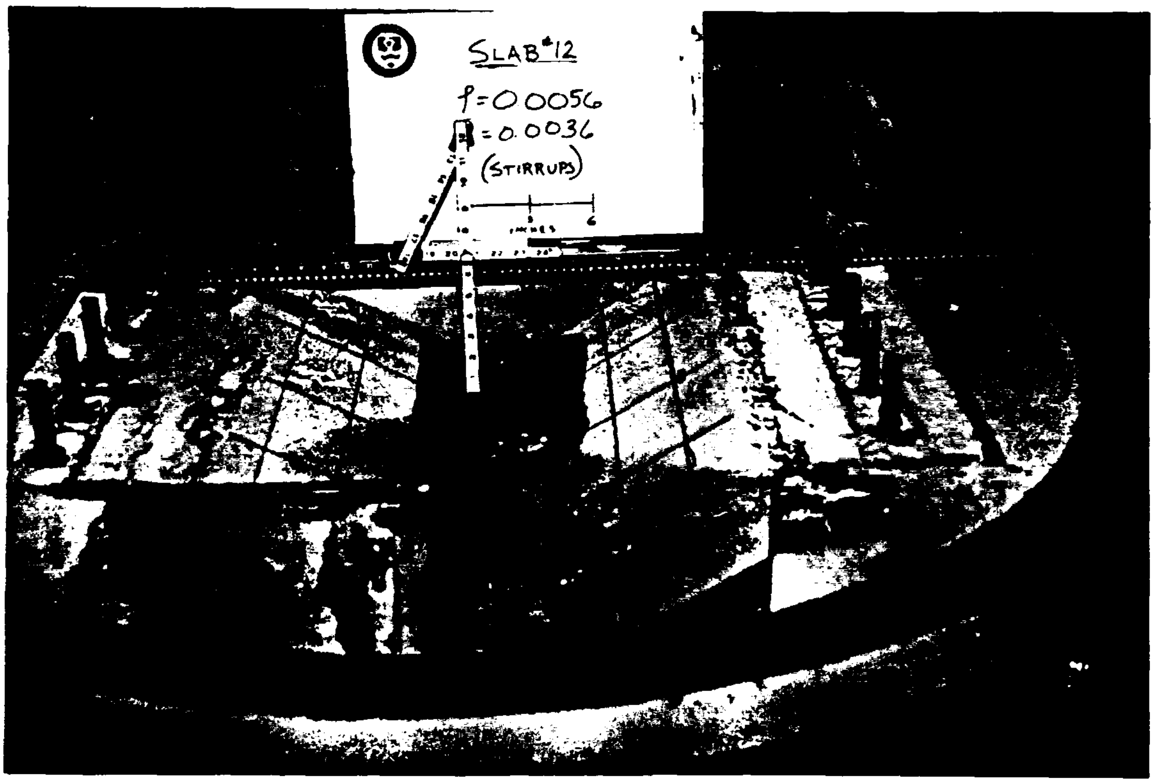


Figure 3.12. Posttest View of Slab No. 12

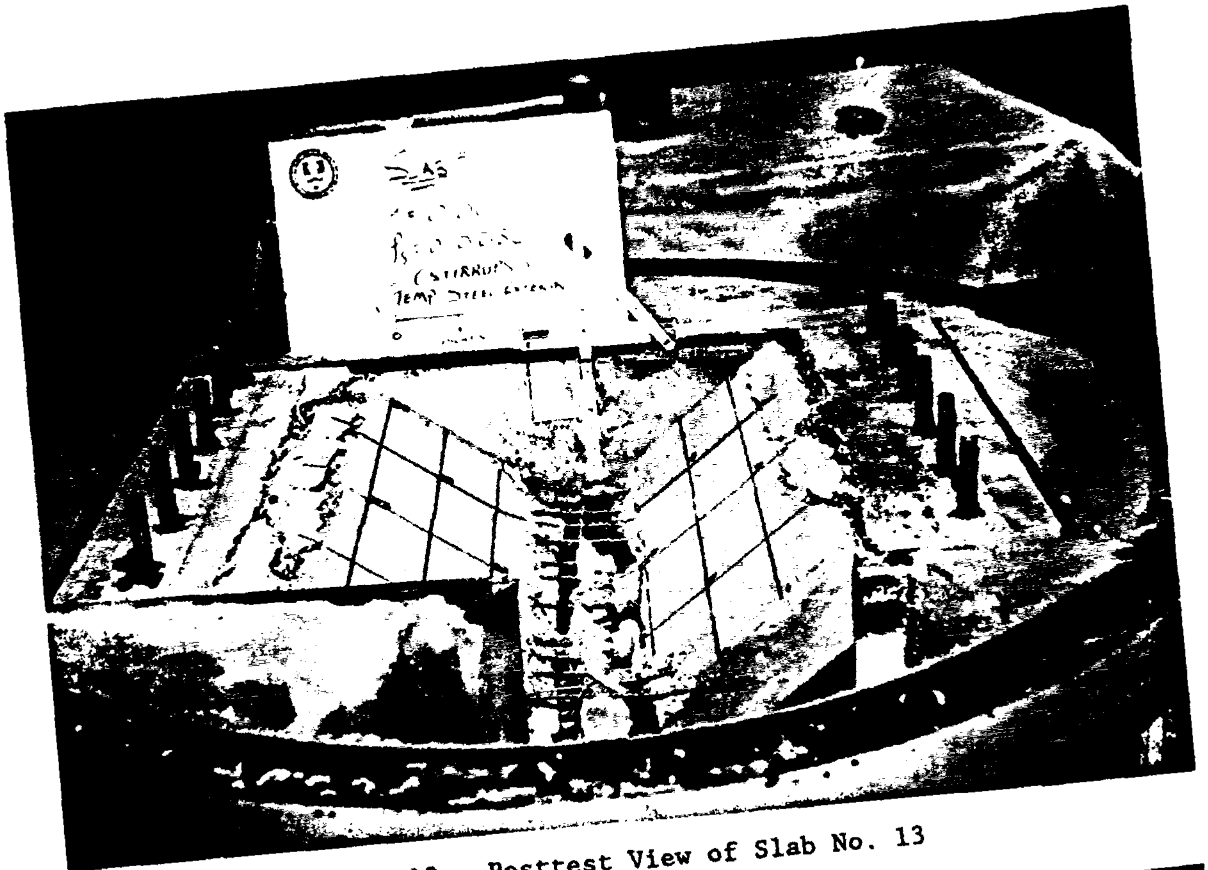


Figure 3.13. Posttest View of Slab No. 13

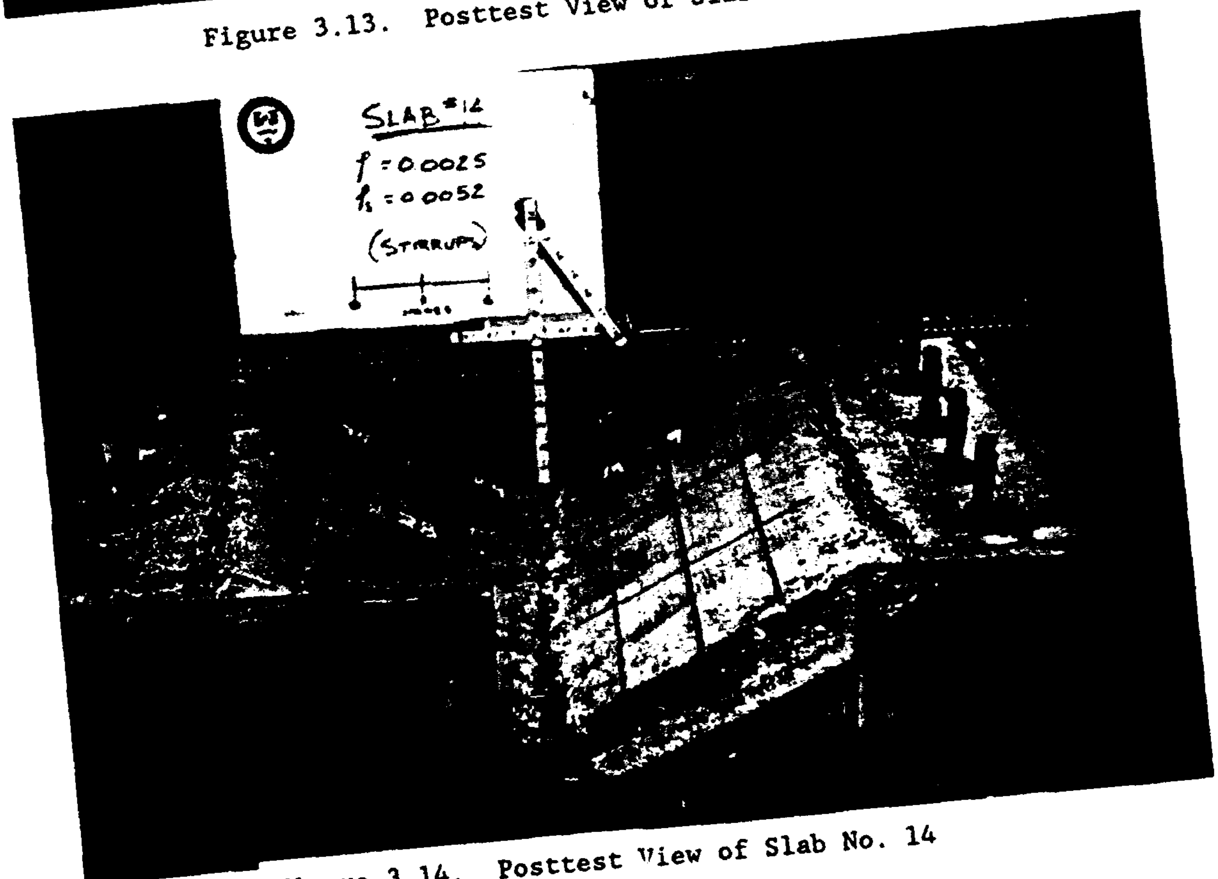


Figure 3.14. Posttest View of Slab No. 14

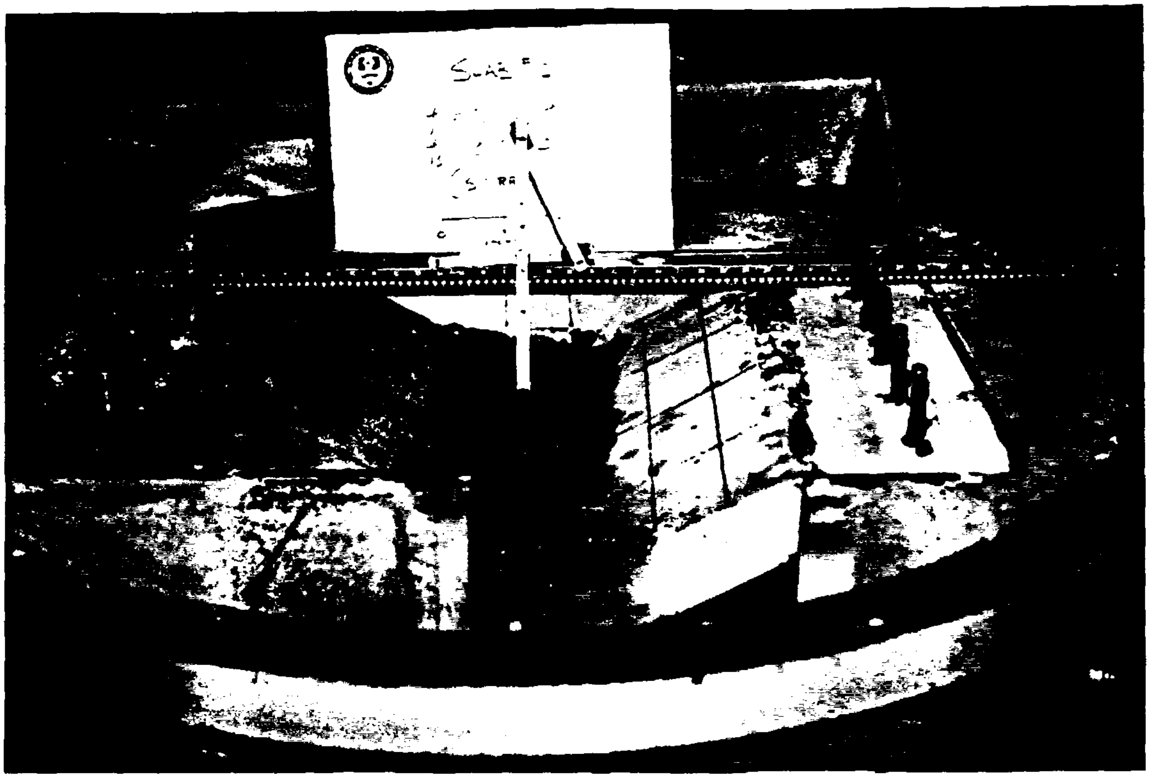


Figure 3.15. Posttest View of Slab No. 15

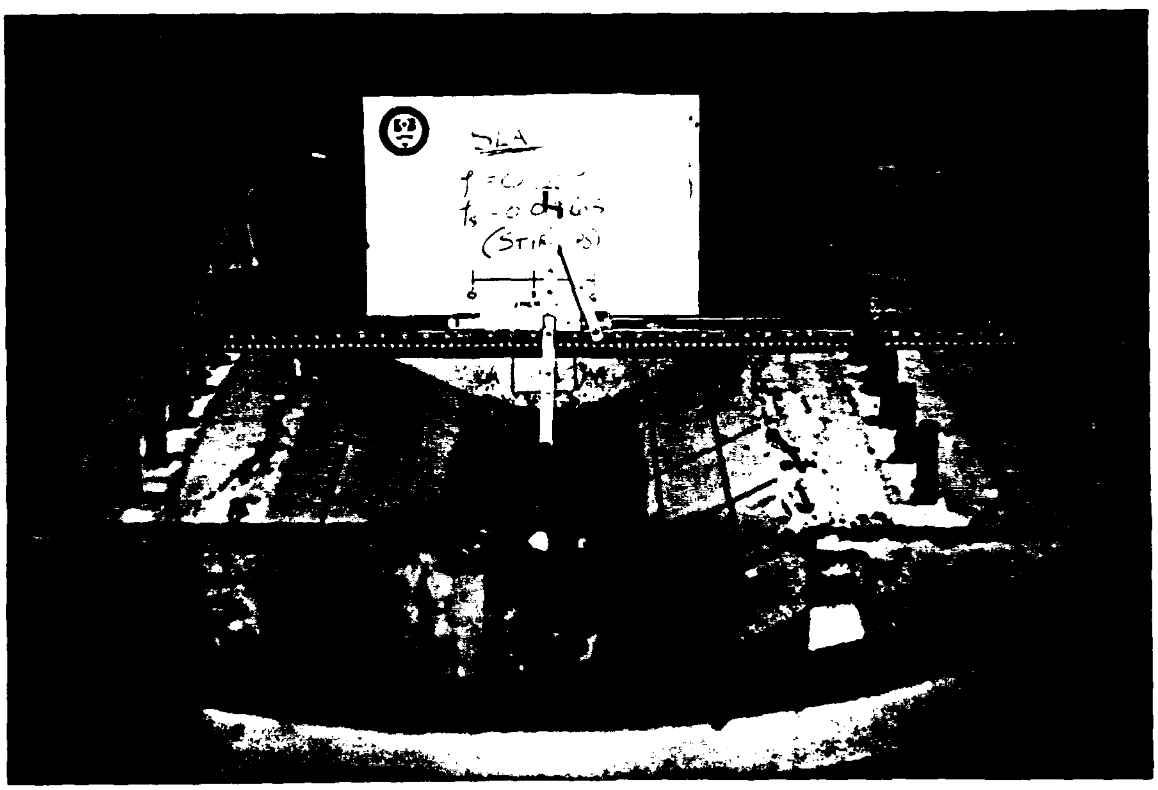


Figure 3.16. Posttest View of Slab No. 16

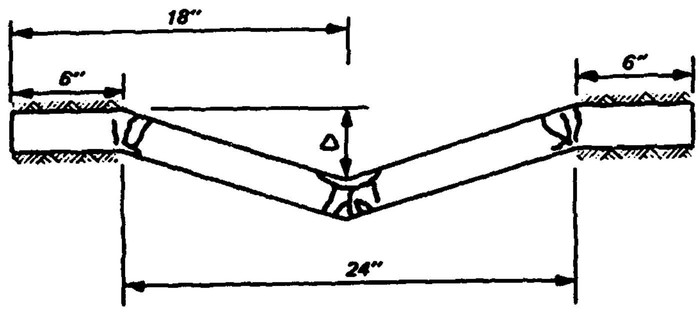


Figure 3.17. General Deformation

Figure 3.18. Posttest View of Undersurface of Slabs

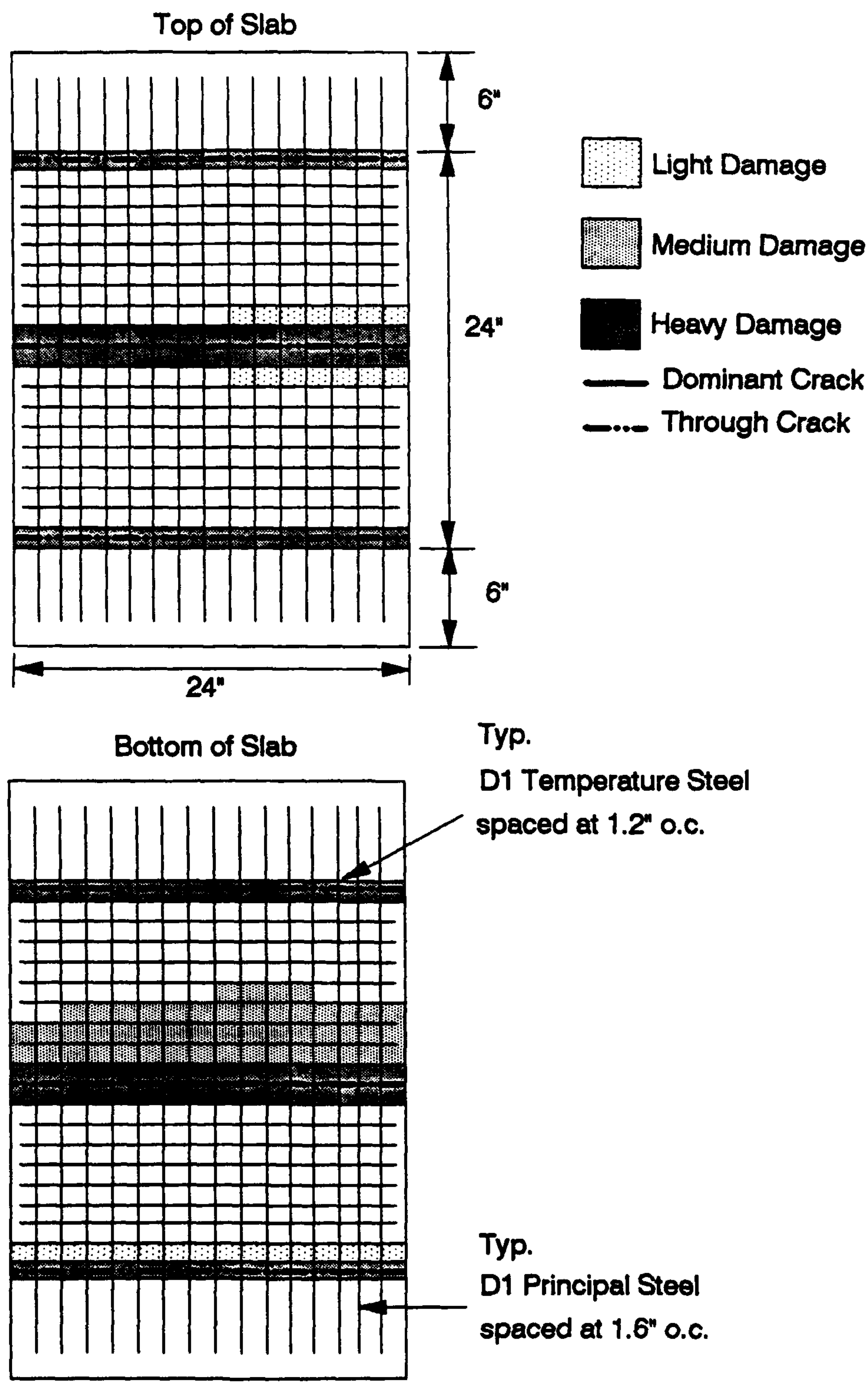


Figure 3.19. Damage Survey of Slab No. 1

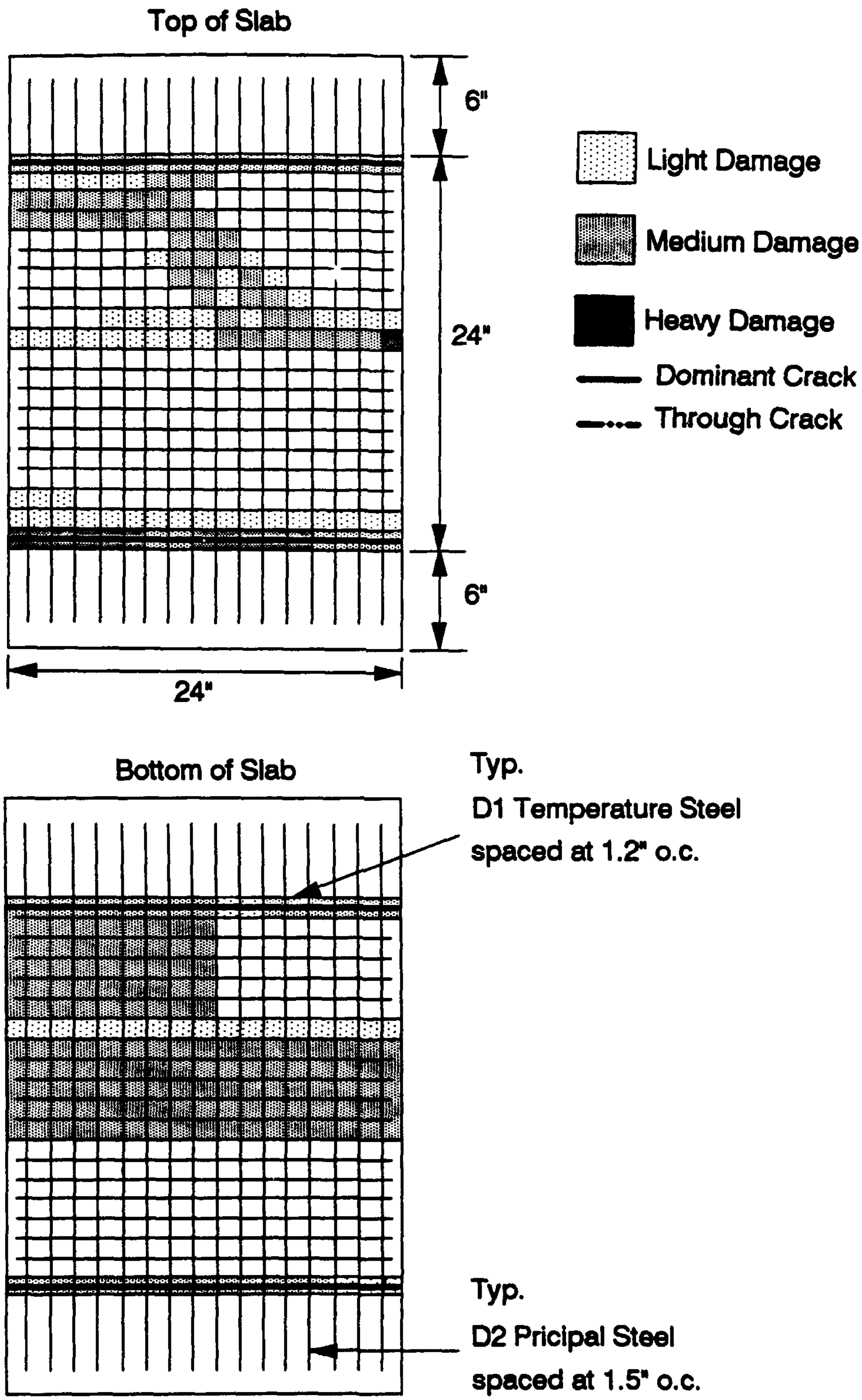


Figure 3.20. Damage Survey of Slab No. 2

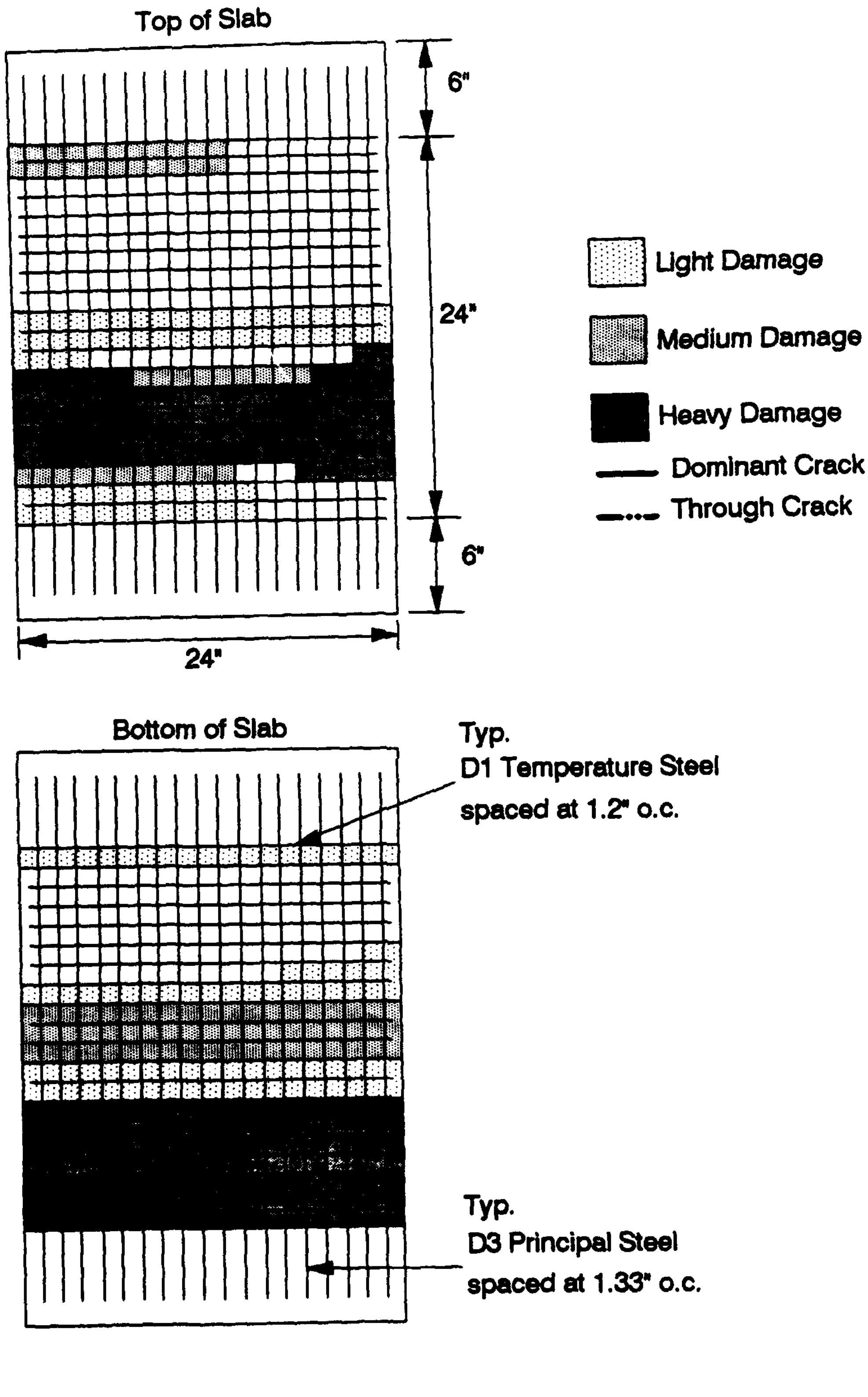


Figure 3.21. Damage Survey of Slab No. 3

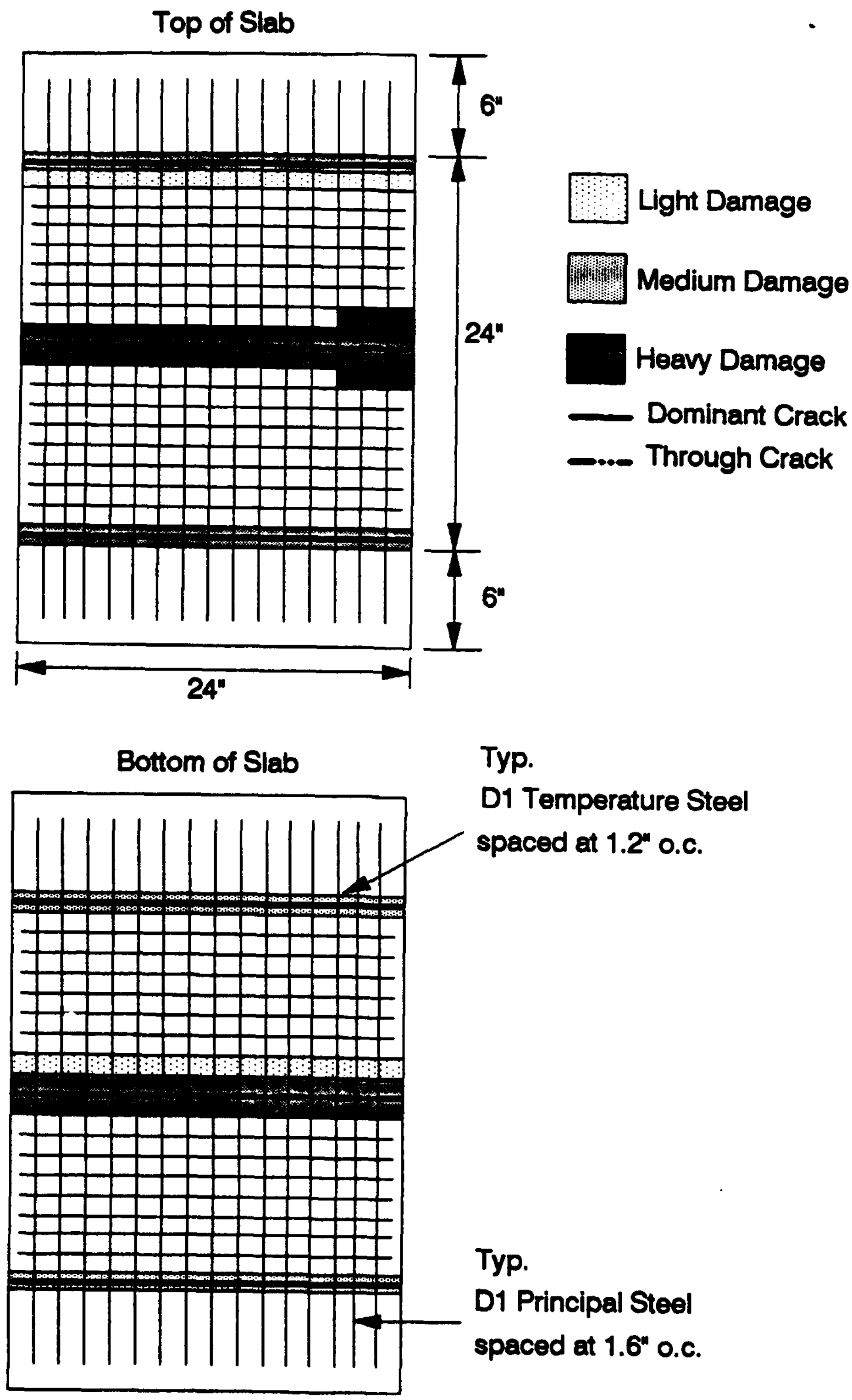


Figure 3.22. Damage Survey of Slab No. 4

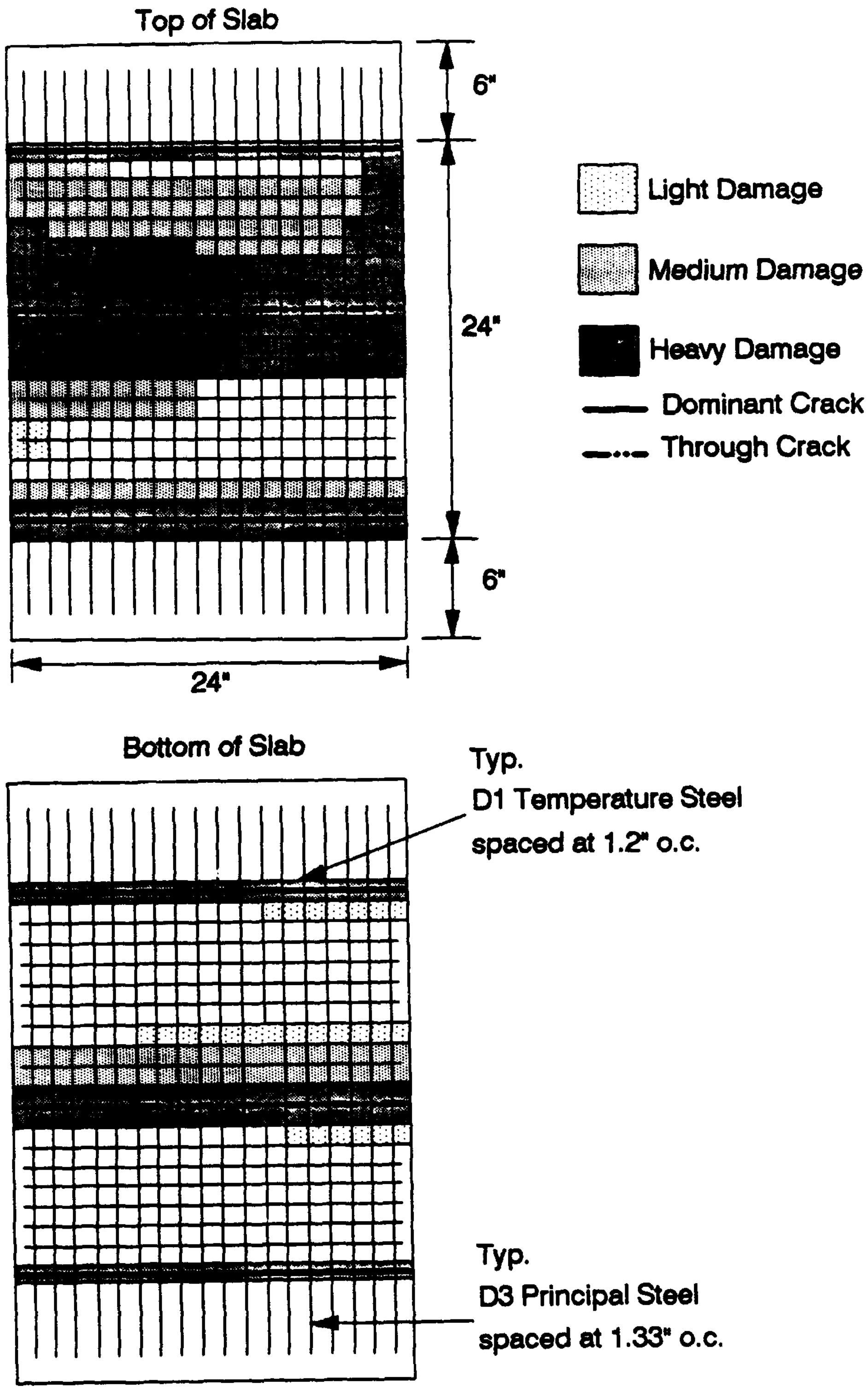


Figure 3.23. Damage Survey of Slab No. 5

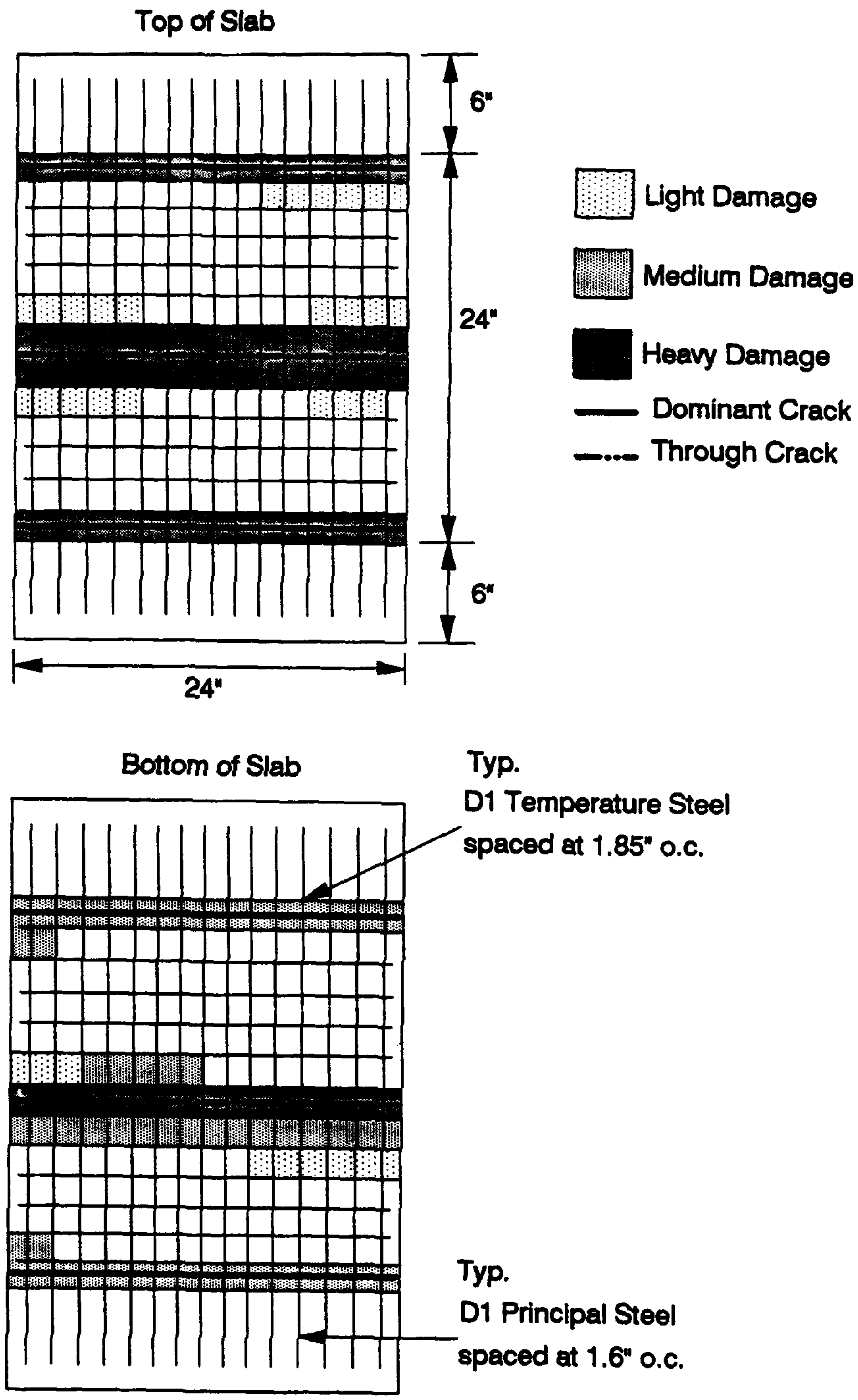


Figure 3.24. Damage Survey of Slab No. 6

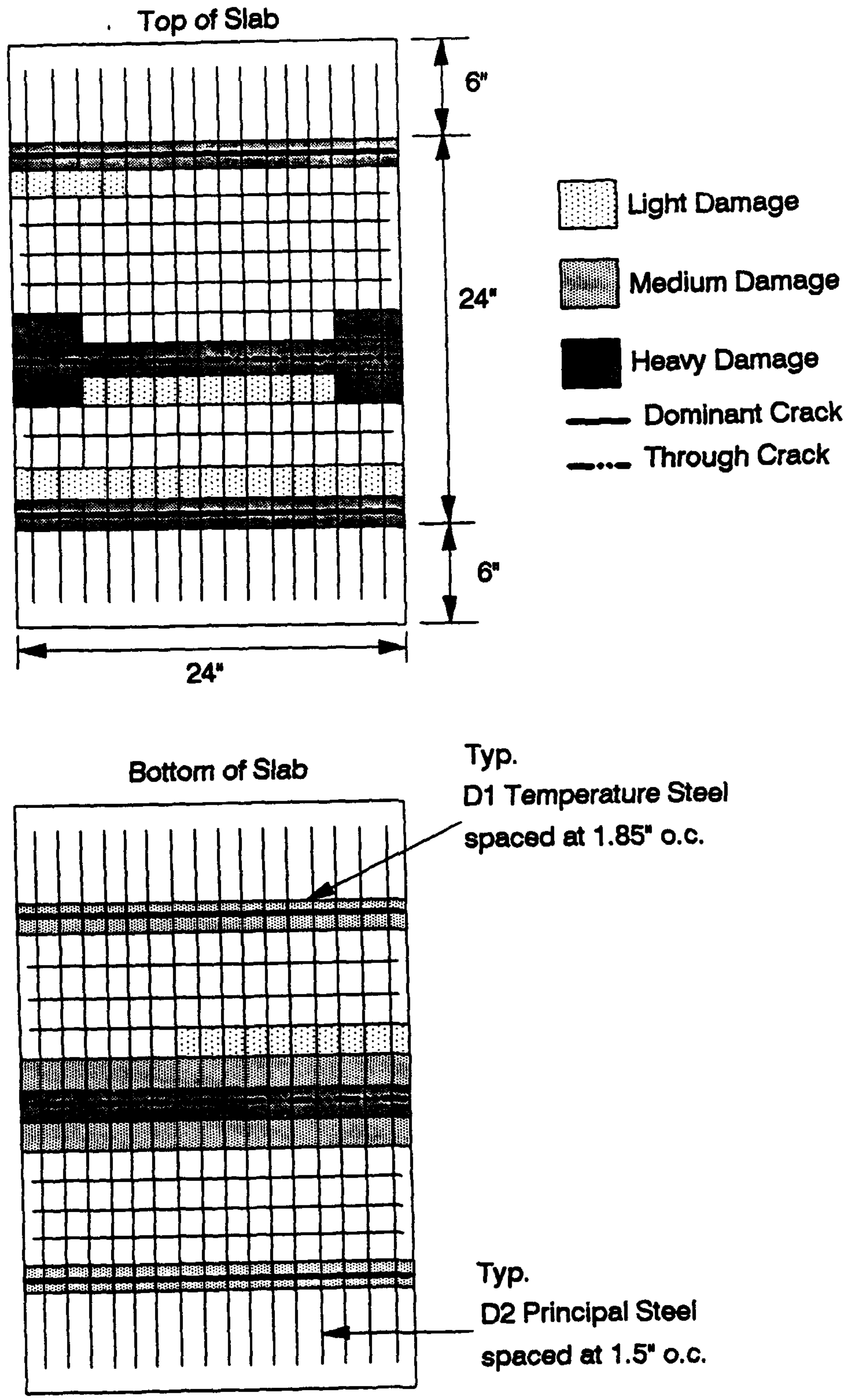


Figure 3.25. Damage Survey of Slab No. 7

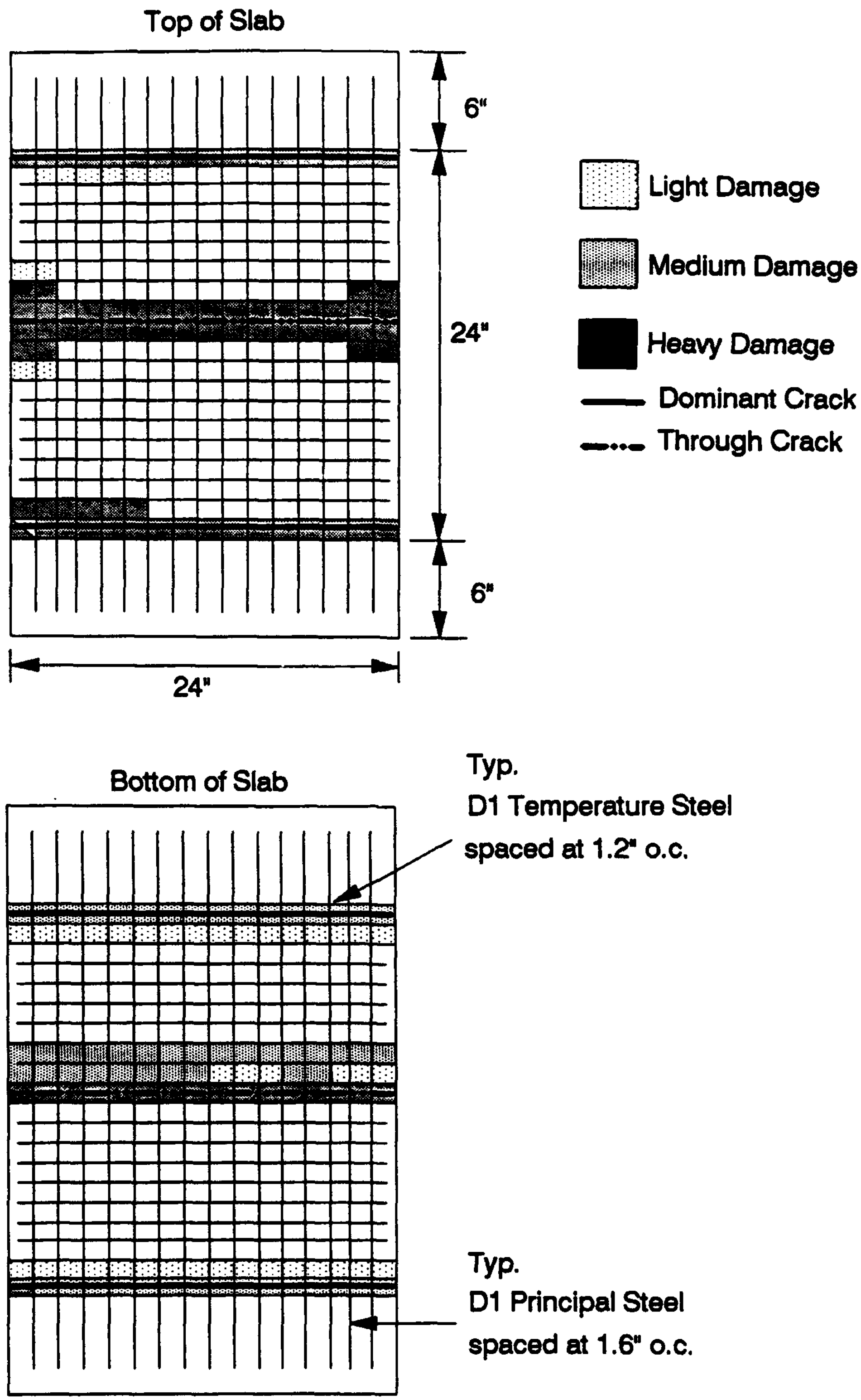


Figure 3.26. Damage Survey of Slab No. 8

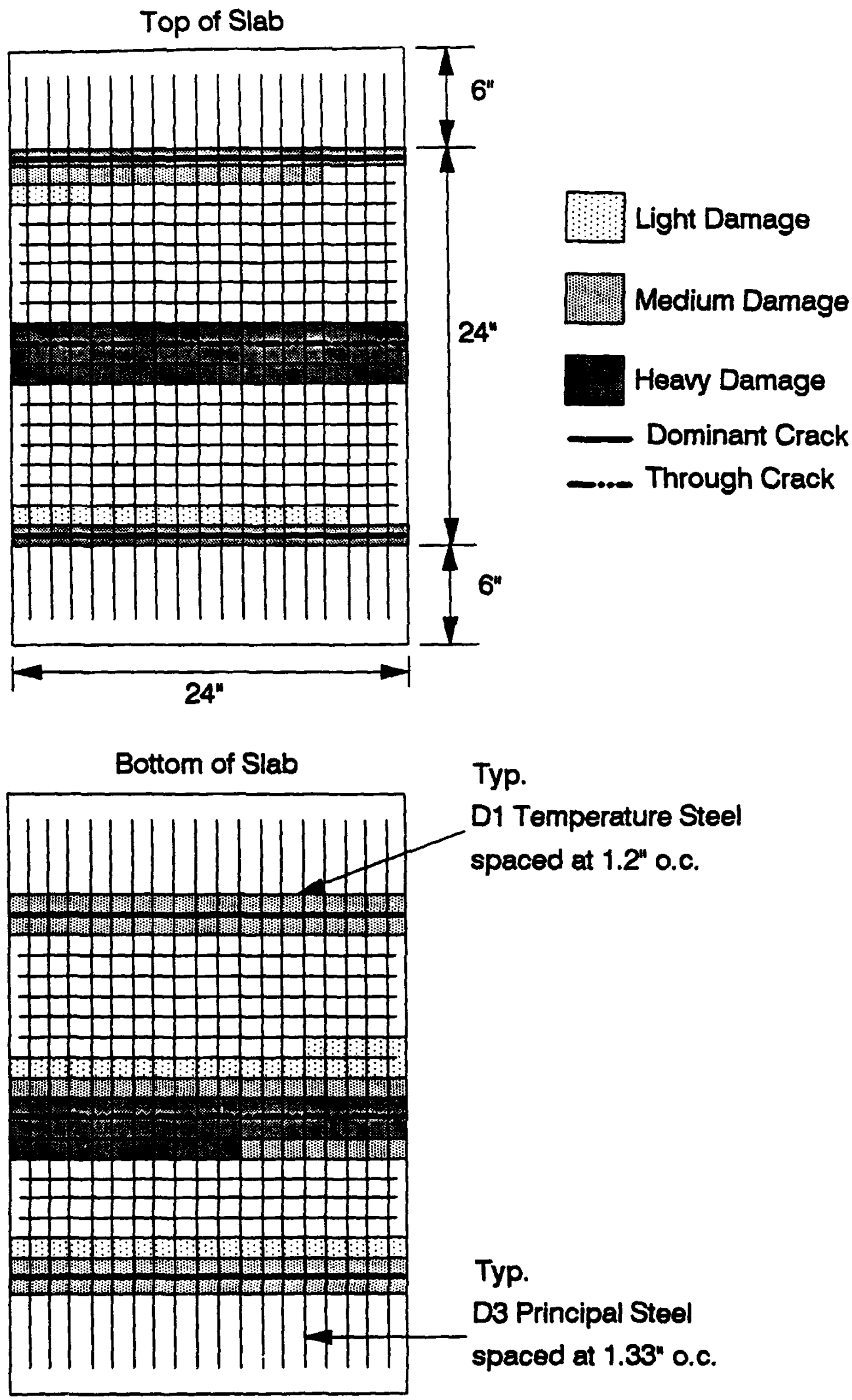


Figure 3.27. Damage Survey of Slab No. 9

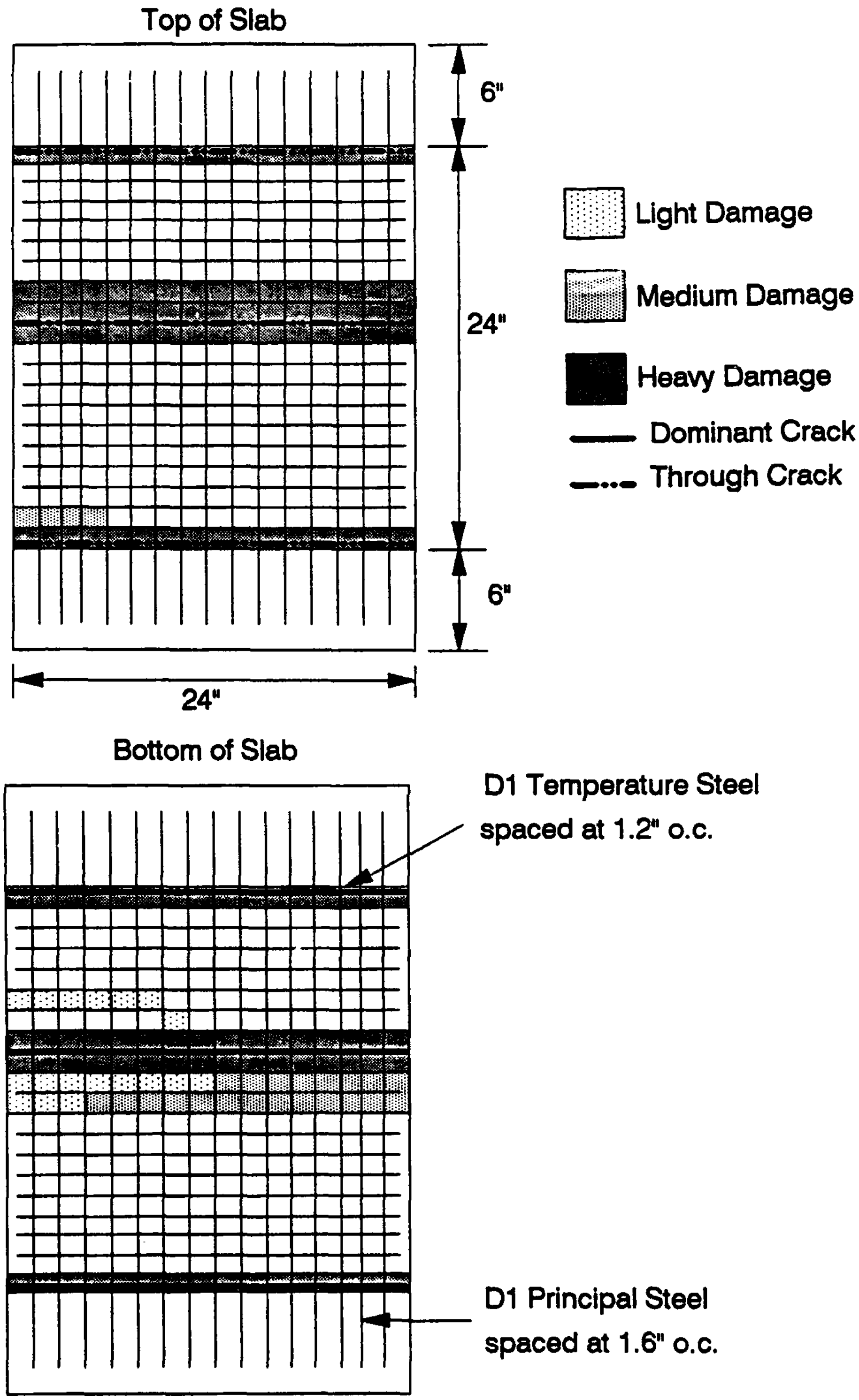


Figure 3.28. Damage Survey of Slab No. 10

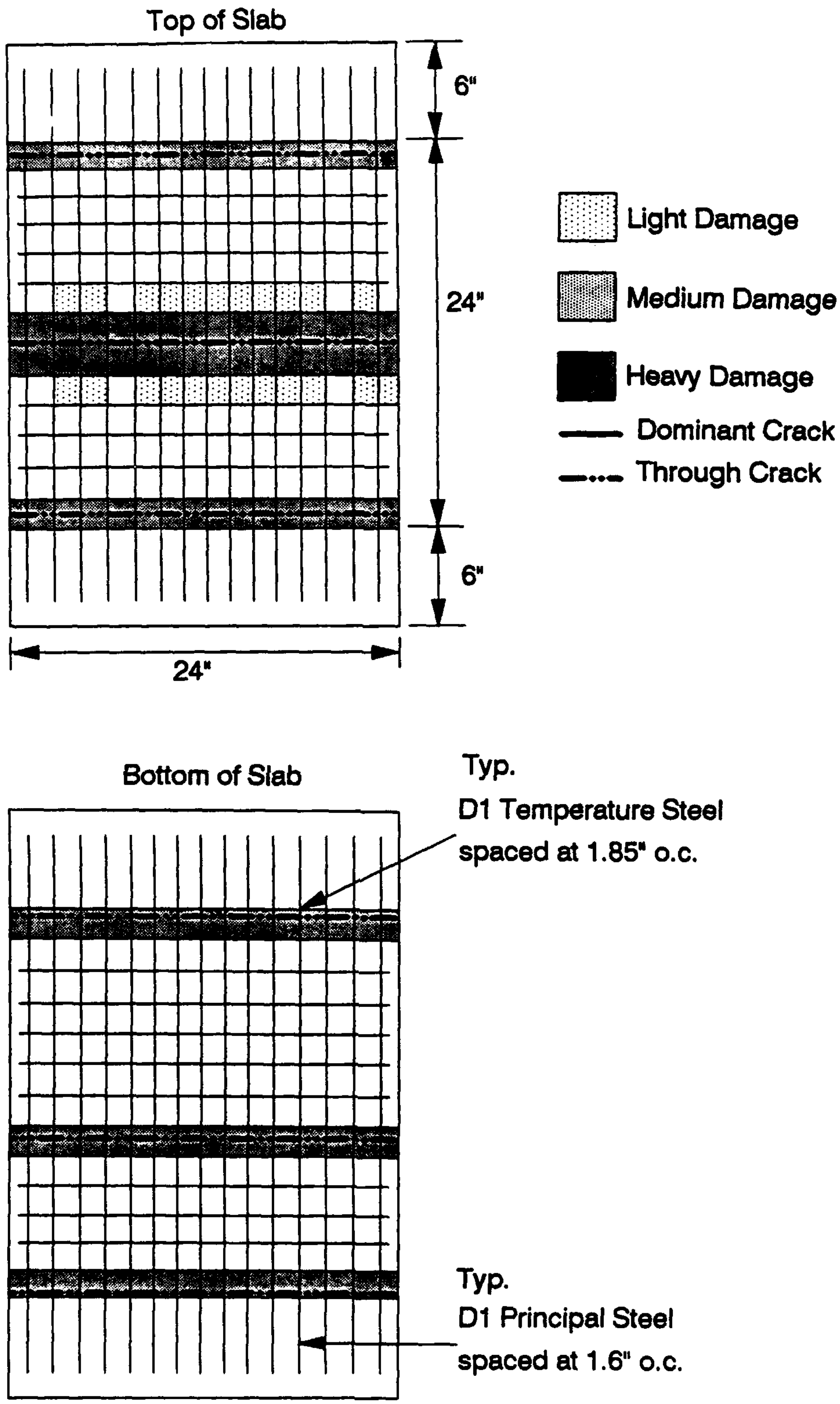


Figure 3.29. Damage Survey of Slab No. 11

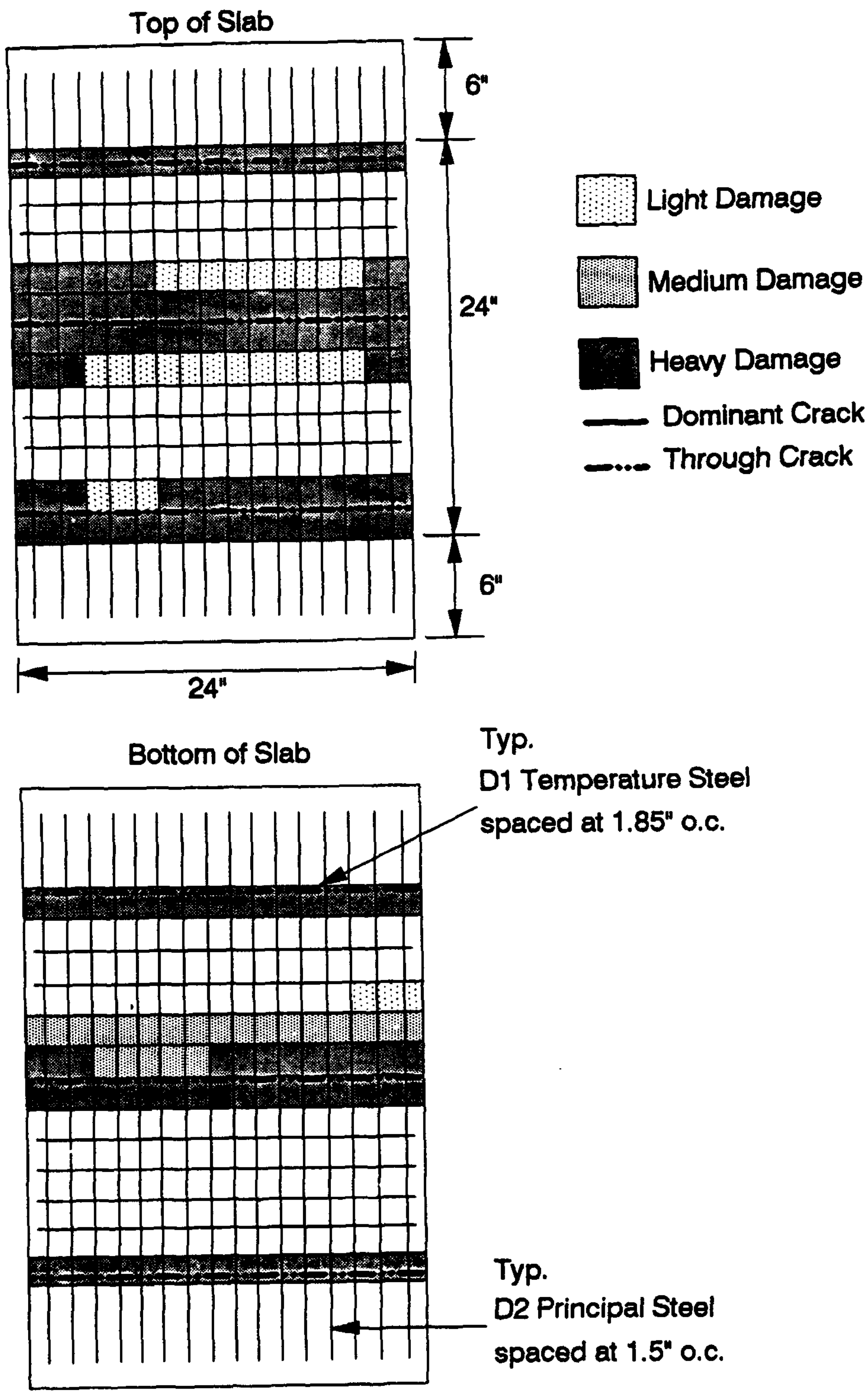


Figure 3.30. Damage Survey of Slab No. 12

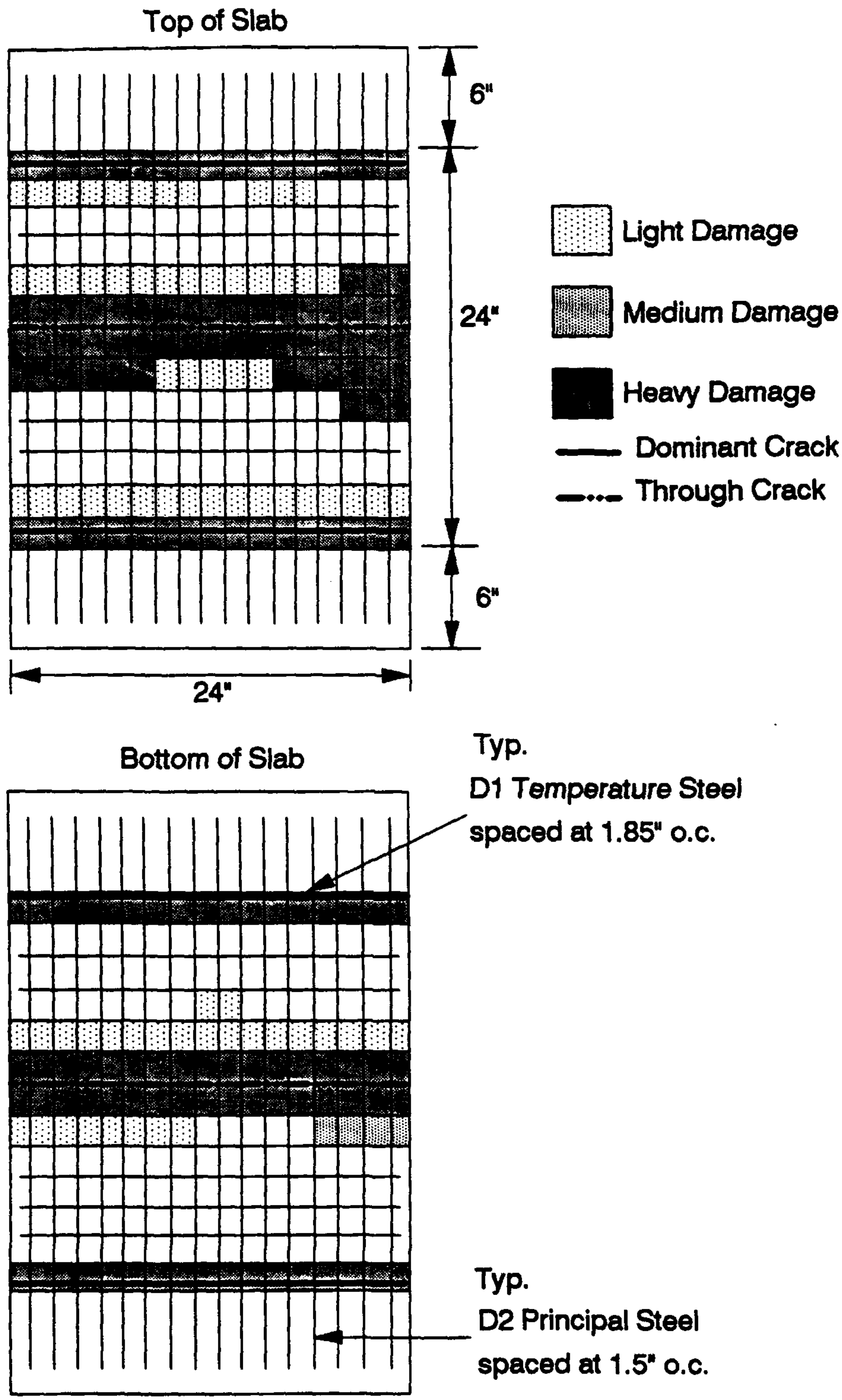


Figure 3.31. Damage Survey of Slab No. 13

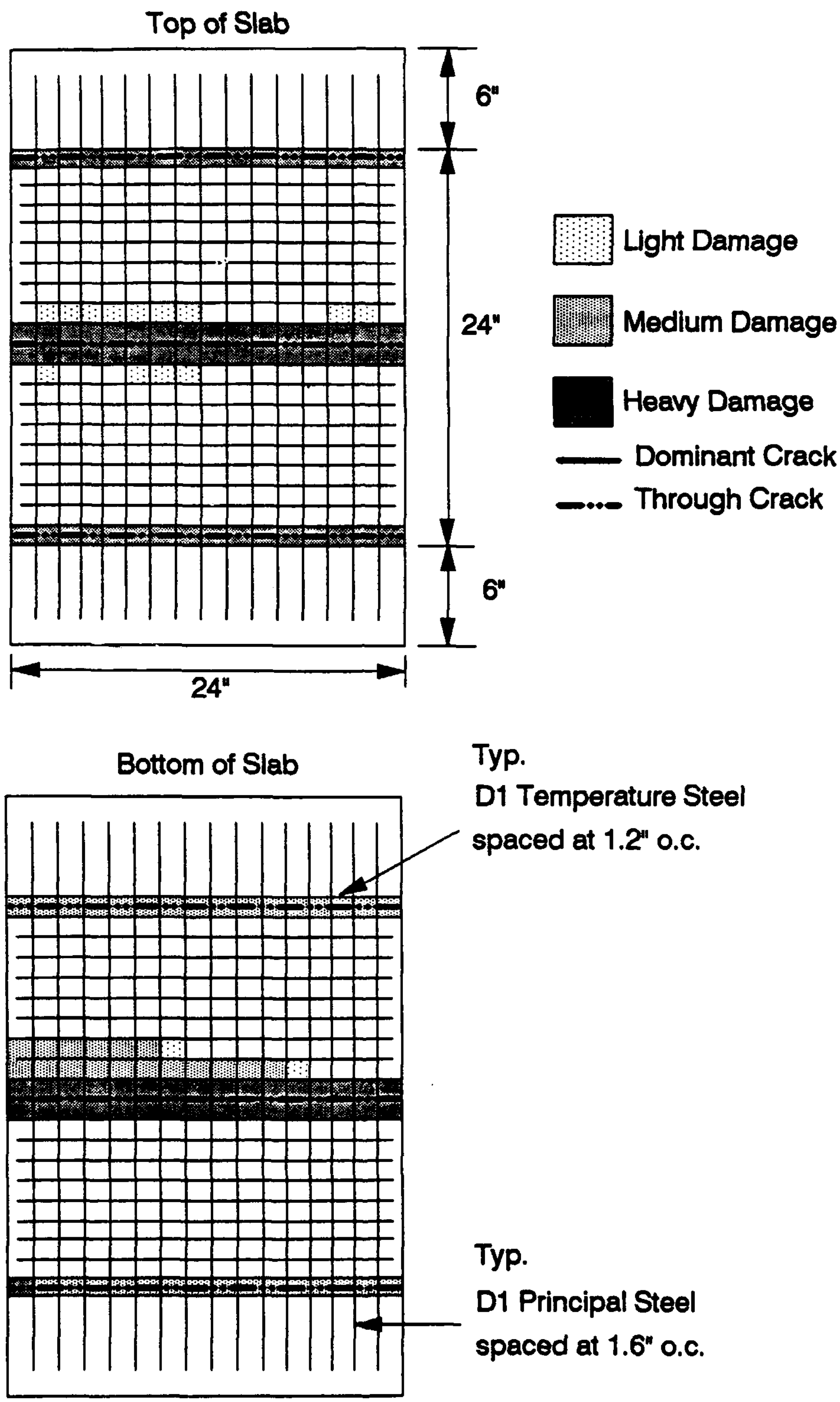


Figure 3.32. Damage Survey of Slab No. 14

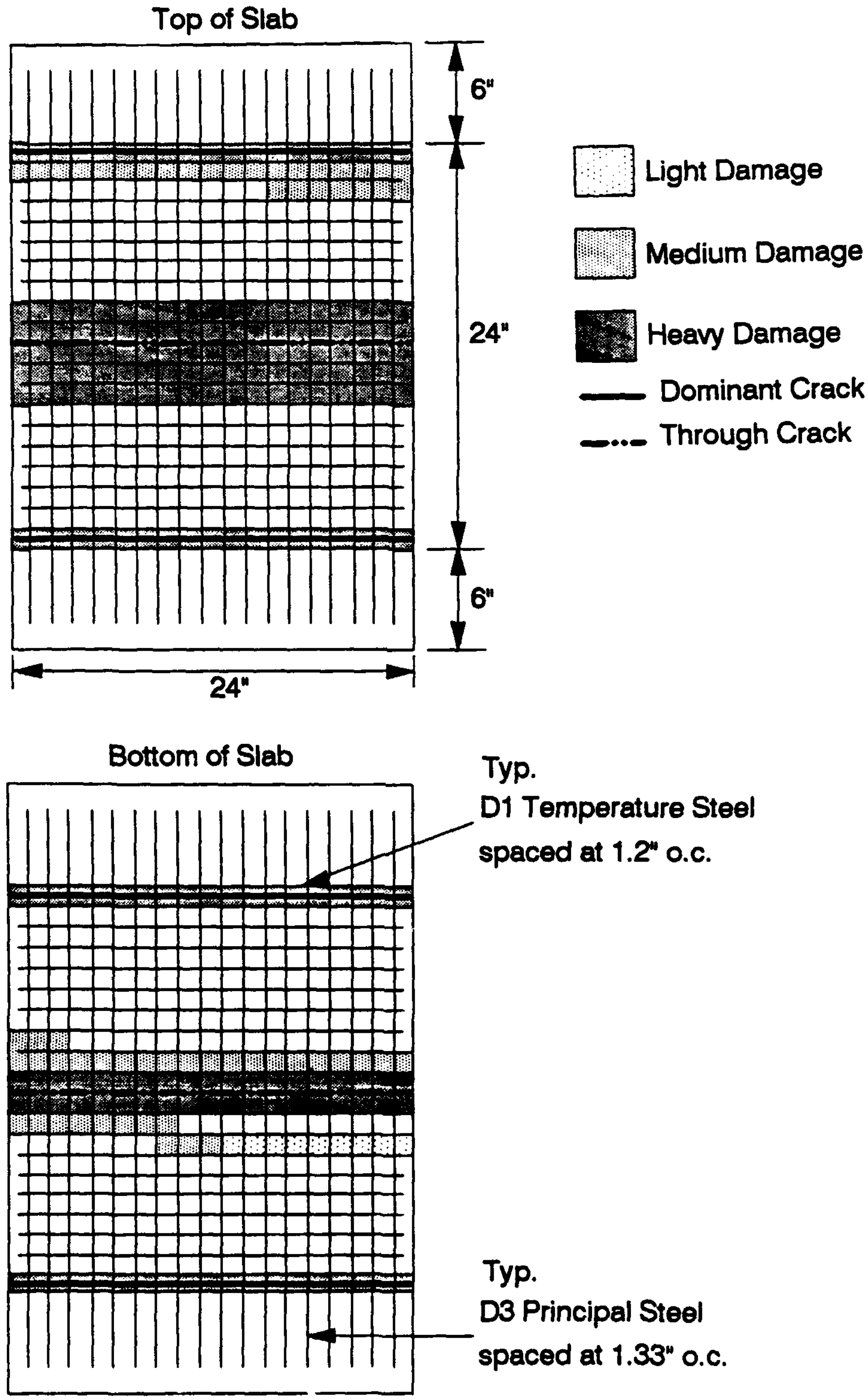


Figure 3.33. Damage Survey of Slab No. 15

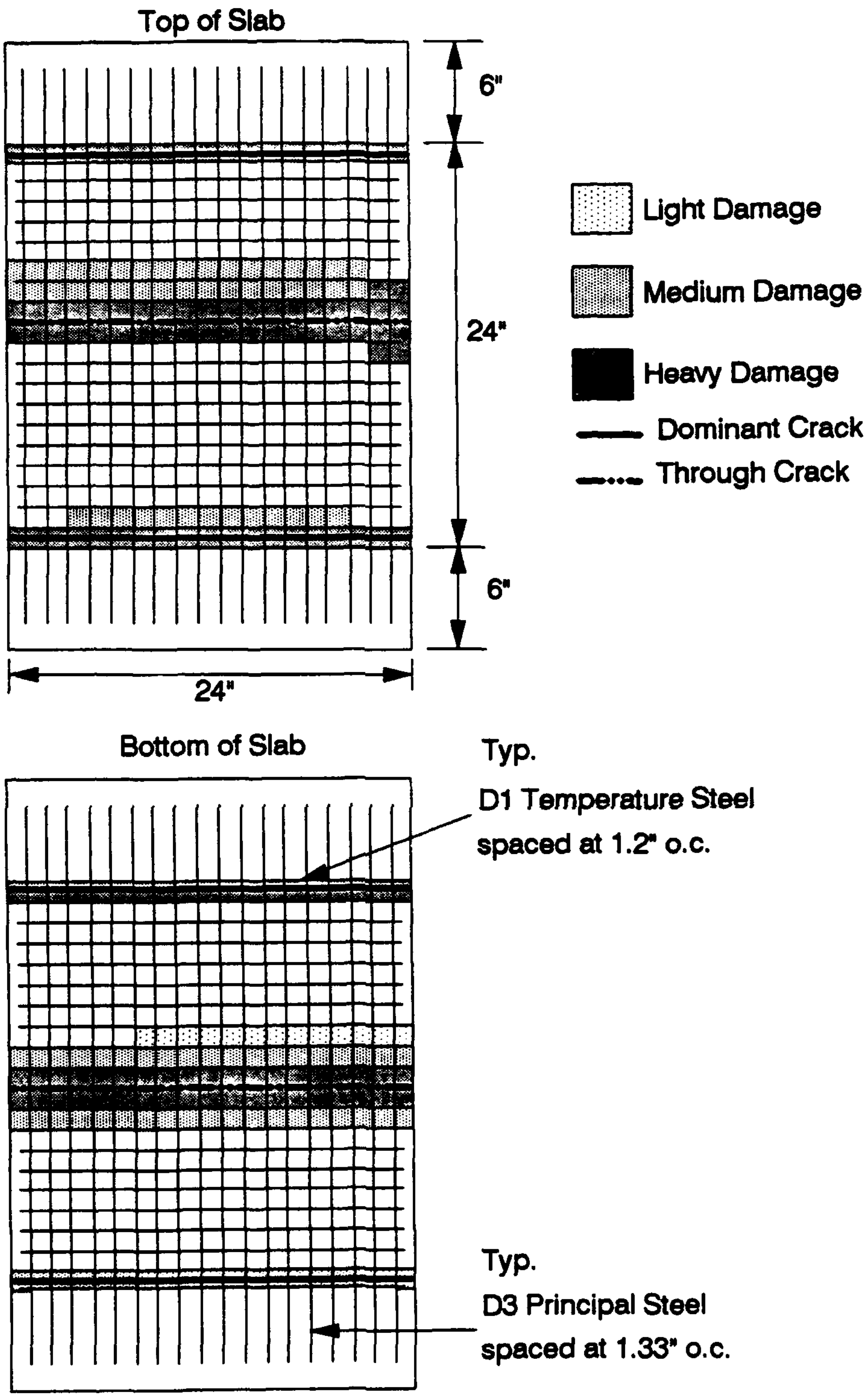


Figure 3.34. Damage Survey of Slab No. 16

PART IV: DISCUSSION

Comparison of Structural Damage and Response

36. Figure 4.1 shows the general shape of the midspan load-deflection curve for the slabs as measured with the pressure and deflection gages. Values of load and deflection at points A through D are given in Table 4.1. During the experimental procedure, the decision to terminate an experiment depended upon the trend of the monitored load-deflection curves; therefore, the deflection at termination varied among the slabs. The full load-deflection curves at midspan were not recorded for slab no. 12, 14, and 16 due to a loss of the deflection gage connection (large cracks formed directly at the connection) to the slab during the experiments. However, the load-deflection curves at the one-quarter span location were successfully recorded for slabs 12, 14, and 16 and will be discussed later.

37. Maximum deflections measured (posttest) at midspan, as presented in Table 3.1, differ from those in Table 4.1. Values presented in Table 3.1 were physically measured after each experiment while those in Table 4.1 were electronically recorded during the experiments. A comparison of the electronically recorded maximum deflection with the posttest measured deflections is presented in Table 4.2.

38. The posttest measured deflection was greater than the electronically recorded maximum deflection for each slab. The primary reason for the discrepancy was the change in the slab's geometry during the experiment. As a slab deflects (as a three-hinged mechanism), a prominent crack forms at midspan. In most cases, the crack forms slightly to the left or to the right of the deflection gage point of connection on the slab. As deflection

continues, the connection point is moved both horizontally and vertically. This horizontal movement tends to pull the cable of the deflection gage out of the gage as opposed to the desired retraction of the cable into the housing. Therefore, error is introduced into the recorded deflection values, particularly at large deflections. The R/M ratio given in Table 4.2 is an indication of the discrepancy in recorded and measured deflections at midspan.

39. Table 4.3 presents values of parameters often used to quantify the response and ductility of a slab. The ratio of midspan deflection (posttest measured) to clear span length (L) is given for each slab. Also, the maximum support rotation for each slab is given.

40. Since the objective of the study is to investigate the effects of shear reinforcement (particularly that of stirrups and lacing bars) on slab behavior, the slabs may be paired by parameter values. As shown in Tables 2.1 and 2.2, slab nos. 1, 2, and 3 were all constructed without shear reinforcement and serve as baseline slabs for this study. The load-response behavior and failure modes of these three slabs varied. The small amount of principal reinforcement in slab no. 1 allowed flexural failure to occur prior to shear failure. The experiment was terminated when it appeared that the load resistance of the slab was rapidly deteriorating and that collapse was impending. This resulted in the well-defined three-hinge mechanism as shown in the photograph of Figure 3.1.

41. The lack of shear reinforcement in slab no. 2 resulted in a combined flexure-shear failure mode. Figure 3.2 shows the diagonal cracking and separation of the concrete through the thickness of the slab as a result of no shear reinforcement being present to stop the crack propagation. It appears that the larger amount of principal reinforcement (as compared to that in slab

no. 1) prevented the flexural failure until shearing action prevailed. Actually, the slab no. 2 experiment was terminated due to a loss in the water pressure that composed the loading. This water leak occurred at one of the supports due to improper sealing around the bolts. Because of the failure mode, it was decided that slab no. 2 should not be reloaded.

42. The large principal reinforcement ratio and the lack of shear reinforcement in slab no. 3 resulted in the dominate shear failure shown in Figure 3.3. The three different failure modes of slab nos. 1, 2, and 3 confirm the need for these three baseline experiments in conjunction with the shear reinforcement study.

43. Slab nos. 4 and 10 differed only in the types of shear reinforcement (lacing in slab no. 4 and stirrups in slab no. 10). Figures 3.4 and 3.10 show that both slabs responded in a well-defined three-hinge mechanism, as was in the case for the baseline slab (slab no. 1) corresponding to these two slabs. The posttest measurements indicated that slab no. 4 was pushed slightly further than slab 10 before experiment termination. Both slabs were pushed to support rotations beyond 22 degrees. The extent of concrete cracking was similar for slab nos. 4 and 10. The small amount of shear reinforcement in these two slabs did not significantly alter the response of the slabs as compared to slab no. 1, which was pushed to a support rotation greater than 20 degrees.

44. Slab nos. 6 and 11 differed only in the types of shear reinforcement (slab no. 1 was the baseline), but the amount of shear reinforcement was greater than in the case of slab nos. 4 and 10. This larger amount of shear reinforcement (categorized as "medium" in Table 2.1) apparently improved the

ductility above that of the baseline slab and above that of the similar slabs with a smaller amount of shear reinforcement (slab nos. 4 and 10) as slab nos. 6 and 10 were capable of being pushed to greater deflections prior to the indications that collapse was impending. Support rotations of approximately 25 and 26 degrees were sustained for slab nos. 6 and 11, respectively. As shown in Figures 3.6 and 3.11, both slabs responded similarly with well-defined three-hinge mechanisms.

45. Slab nos. 8 and 14 represented a further increase in the amount of shear reinforcement (termed "large" in Table 2.1). Both of these slabs sustained support rotations of approximately 25 degrees. Slab no. 14 was one of the three slabs in which the midspan deflection gage became disconnected during the experiment; however, Table 4.4 indicates that the response of the two slabs were very similar throughout the entire range of deflections, as based on the one-quarter span data. This is supported by the similar damage levels presented in Figures 3.8 and 3.14. Additionally, the damage levels and responses for these two slabs were similar to those of slab nos. 6 and 11, indicating no significant differences in the effects of the "medium" and "large" amounts of shear reinforcement on slab behavior.

46. Only the "medium" (as given in Table 2.1) category of shear reinforcement was investigated for the "medium" amount of principal reinforcement (baseline is slab no. 2). Slab nos. 7 and 12 differed only in that lacing and stirrups were used for slab nos. 7 and 12, respectively. Slab nos. 7 and 12 were pushed to support rotations of approximately 21 and 25 degrees, respectively. Table 4.4 indicates very similar behavior for the two slabs. From Figures 3.7 and 3.12, it is obvious that the "medium" category of shear reinforcement was sufficient to prevent shear failure (as opposed to the flexure\shear

failure in the baseline slab no. 2) and enhance the ductility of the slabs. Also, the photographs indicate a smoothing of the midspan crack region of the three-hinge mechanism when compared to the previously discussed slabs that contained the "small" amount of principal reinforcement.

47. Slab no. 13 was similar to slab no. 12, differing only in the placement of the temperature reinforcement. The temperature reinforcement was placed exterior to the principal reinforcement in slab no. 13, but interior to the principal reinforcement in slab no. 12. A previous study (Woodson, 1985) indicated that the exterior placement of the temperature reinforcement may enhance the ductility of a slab, possibly overshadowing some effects of shear reinforcement. Although slab no. 13 was pushed slightly further than slab no. 12, its response was not significantly different. Figure 3.13 shows a significant loss of concrete in the compressive crushing zone at midspan. However, the bending of the principal reinforcement resembles the midspan zone of slab no. 12 as shown in Figure 3.12. The large support rotation of 30 degrees for slab no. 13 resulted in the concrete falling from the reinforcement. A small core of concrete remained attached to the reinforcement, primarily due to the "medium" amount of shear reinforcement that was present in the form of stirrups.

48. Slab nos. 5 and 15 each contained a "small" amount of shear reinforcement in the form of lacing and stirrups, respectively. These slabs contained a large amount of principal reinforcement for which the baseline slab was slab no. 3. Although a water leak caused termination of the experiment at a support rotation of approximately 24 degrees for slab no. 15, Figures 3.5 and 3.15 indicate that the failure modes for the two slabs were similar. Slab no. 5 was pushed to a support rotation of approximately 30 degrees. Although only

a small amount of shear reinforcement was used in these slabs, the failure mode was primarily that of flexure rather than the shear failure that occurred in the baseline slab no. 3.

49. "Large" amounts of both principal reinforcement and shear reinforcement were used in slab nos. 9 and 16. These slabs were pushed to support rotations of approximately 23 to 24 degrees. Although Figures 3.9 and 3.16 indicate damage levels similar to that of Figures 3.5 and 3.15, the large amounts of shear reinforcement in slab nos. 9 and 16 confined the concrete significantly better than the small amounts of shear reinforcement in slab nos. 5 and 15. It is well known that concrete confinement contributes to the ductility of a reinforced concrete member. In this study, the better confinement did not prohibit the rupture of the principal reinforcement; however, the confinement is beneficial in that it significantly aids in the reduction of concrete debri that may injure personnel or damage sensitive equipment inside actual structures.

Ultimate Capacity

50. The ultimate capacity of a reinforced concrete member is the peak load resistance sustained prior to "snap-through". In this report, the resistance at the point "A" in Figure 4.1 corresponds to the ultimate capacity. The ultimate capacity is enhanced in slabs whose edges are restrained against lateral movement. As the slab deflects, changes in geometry cause the slab's edges to tend to move outward and to react against the stiff boundary elements. The membrane forces enhance the flexural strength of the slab sections at the yield lines. It is generally known that the compressive membrane forces may increase the strength of the slab sections at the yield

lines by several times. Studies by several researchers (Park, 1964; Morley, 1967; Hung and Nawy, 1971; and Isaza, 1972) indicate a wide range of values for the ratio of the deflection associated with P_A to the slab thickness. The range given for this ratio is broad when the above-mentioned researchers' values are considered. This range includes values from approximately 0.17 to 1.0.

51. Table 4.5 summarizes the ultimate capacities experimentally obtained for the sixteen slabs. The slabs are grouped according to their reinforcement details. The yield-line values (ultimate capacity if edges are not restrained against lateral movement) are given in Table 4.5 for comparison. Compressive membrane forces acted to increase the ultimate capacities of the slabs from approximately 1.2 to 3.5 times the computed yield-line strengths. Also, the ratio Δ_A/t varied among the slabs with values from approximately 0.15 to 0.35. There was no obvious pattern for the values of Δ_A/t in relation to the slab construction parameters. However, it is apparent from Table 4.5 that the compressive membrane enhancement was greatest for the slabs with the smallest principal reinforcement ratio.

52. In general, the ultimate capacities of the slabs followed the pattern that the baseline slabs (nos. 1, 2, and 3) had the lowest values, followed by the corresponding slab with stirrups, and then by the corresponding slab with lacing. For example, the ultimate capacities of slab nos. 1, 10, and 4 were 57, 63, and 71 psi, respectively. However, this pattern did not hold for slab nos. 7, 12, and 13, all of which contained "medium" amounts of both principal and shear reinforcement. Also, the ultimate capacities were approximately equal for slab nos. 8 and 14, both contained a "small" amount of principal reinforcement and a "large" amount of shear reinforcement.

Table 4.1. Midspan Load-Deflection Summary

Slab	P_A (psi)	Δ_A (in)	P_B (psi)	Δ_B (in)	P_C (psi)	Δ_C (in)	P_D (psi)	Δ_D (in)
1	57	0.52	8	2.41	8	2.41	23	3.61
2	87	0.80	44	1.10	44	1.10	53	1.65
3	106	0.45	57	0.51	57	0.51	88	2.18
4	71	0.80	11	2.31	11	2.96	31	4.36
5	135	0.89	70	1.69	27	3.88	41	4.96
6	88	0.79	10	2.58	10	2.58	31	4.80
7	83	0.88	38	2.32	22	3.61	15	4.00
8	64	1.00	8	2.50	8	3.10	27	4.50
9	143	1.06	18	2.85	18	2.85	77	4.22
10	63	0.65	3	2.33	8	3.59	25	4.77
11	63	0.91	1	2.65	1	2.65	22	5.00
12	85	1.10	19	3.10	*	*	*	*
13	89	0.74	25	2.00	25	3.19	44	4.63
14	64	0.87	5	2.60	*	*	*	*
15	130	0.81	58	2.30	14	3.11	75	4.00
16	*	*	*	*	*	*	*	*

* Large crack formed directly at deflection gage connection on slab, causing loss of connection.

Table 4.2. Midspan Deflection (taken from Tables 3.1 and 4.1)

Slab	Posttest Measured (M) (in)	Electronically Recorded (R) (in)	R/M
1	4.4	3.61	0.82
2	1.7	1.65	0.97
3	2.2	2.18	0.99
4	5.5	4.36	0.79
5	7.0	4.96	0.71
6	5.5	4.80	0.87
7	4.5	4.0	0.89
8	5.5	4.50	0.82
9	5.3	4.22	0.80
10	5.0	4.77	0.95
11	5.9	5.00	0.85
12	5.7	-	-
13	7.0	4.63	0.66
14	5.7	-	-
15	5.3	4.00	0.75
16	5.1	-	-

Table 4.3. Support Rotation and Ratio of Midspan Deflection to Clear Span

Slab	Δ/L (percent)	$\emptyset$ (degrees)
1	18.3	20.1
2	7.1	8.1
3	9.2	10.4
4	22.9	24.6
5	29.2	30.3
6	22.9	24.6
7	18.8	20.6
8	22.9	24.6
9	22.1	23.8
10	20.8	22.6
11	24.6	26.2
12	23.8	25.4
13	29.2	30.3
14	23.8	25.4
15	22.1	23.8
16	21.3	23.0

Table 4.4. Quarter-span Load-Deflection Summary

Slab	P_A (psi)	Δ_A (in)	P_B (psi)	Δ_B (in)	P_C (psi)	Δ_C (in)	P_D (psi)	Δ_D (in)
7	83	0.43	22	1.05	11	1.70	42	1.98
12	85	0.56	25	1.13	19	1.85	38	2.51
8	64	0.45	8	1.10	9	1.43	27	2.13
14	64	0.45	5	1.14	5	1.54	23	2.14
9	143	0.48	16	1.36	16	1.36	77	2.28
16	128	0.51	7	1.32	7	1.32	79	2.37

Table 4.5. Ultimate Capacity

Slab	Yield-Line (psi)	P_A (psi)	P_A/Yield-Line	Δ_A (in)	Δ_A/t	Shear Rein.
1	25	57	2.3	0.57	0.19	none
2	55	87	1.6	0.80	0.27	none
3	92	106	1.2	0.45	0.15	none
4	25	71	2.8	0.80	0.27	lacing
10	25	63	2.5	0.65	0.22	stirrups
5	92	135	1.5	0.89	0.30	lacing
15	92	130	1.4	0.81	0.27	stirrups
6	25	88	3.5	0.79	0.26	lacing
11	25	63	2.5	0.91	0.30	stirrups
7	55	83	1.5	0.88	0.29	lacing
12	55	85	1.5	1.10	0.37	stirrups
13	55	89	1.6	0.74	0.25	stirrups
8	25	64	2.6	1.00	0.33	lacing
14	25	64	2.6	0.87	0.29	stirrups
9	92	143	1.6	1.06	0.35	lacing
16	92	128	1.4	-	-	stirrups

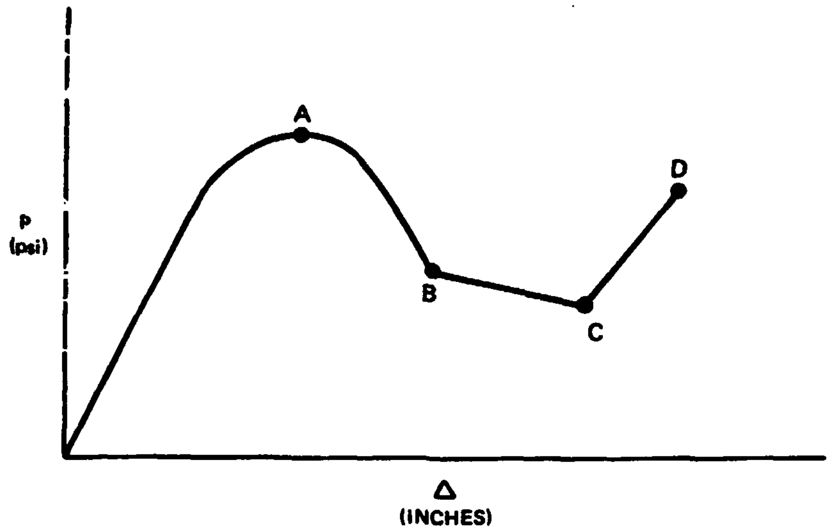


Figure 4.1. General Load-Deflection Curve

PART V: CONCLUSIONS AND RECOMMENDATIONS

General

53. Sixteen one-way reinforced concrete slabs were uniformly and statically loaded, with water pressure, to large deflections to investigate the comparative effects of stirrups and lacing bars on the behavior of one-way slabs.

Conclusions

54. Laterally restrained one-way reinforced concrete slabs are capable of sustaining support rotations greater than 20 degrees if shear failure is prohibited. For slabs having approximately 1.0 percent principal reinforcement, shear reinforcement is needed to avoid shear failure. A small amount of shear reinforcement (0.31 percent) was shown to be adequate to prohibit shear failure in these slabs.

55. The load-deflection curves for the slabs were very similar when compared for a laced slab and a slab with stirrups (all other parameters held constant). However, the experiments indicated (was not true for all of the experiments) that a laced slab may possess a slightly greater ultimate capacity than a similar slab with stirrups.

56. The primary conclusion from the experimental program is that lacing and stirrups contribute to the ductility of a one-way slab in a similar manner and at a similar magnitude. Failure modes were nearly identical for the slabs comparing the two types of shear reinforcement. Consequently, based on this series of statically loaded slabs, design guidelines restricting the use of stirrups significantly more than the use of lacing, for the purpose of improving large-deflection behavior, are overly conservative.

Recommendations

57. This experimental program formed the base of data showing the similar effects of lacing and stirrups. Experiments using dynamic loading conditions should by conducted to validate the findings of this study and to further study the effects of lacing and stirrups on slab behavior. Additionally, this study should be extended to slabs with other L/d values, particularly "deep" (L/d < 5) members.

58. Agencies have been identified that are interested in promoting further study or analysis of the data generated in this experimental program. These avenues should be pursued and the slab designs and experimental data should be analyzed in great detail, possibly through the use of finite-element techniques.

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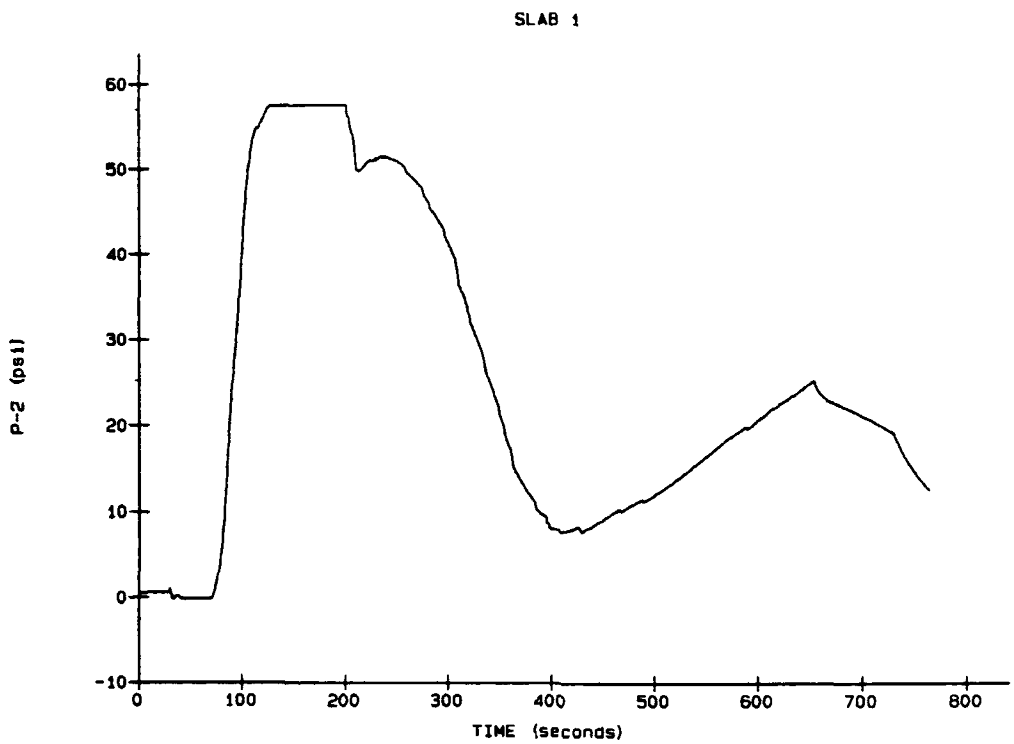
APPENDIX A

DATA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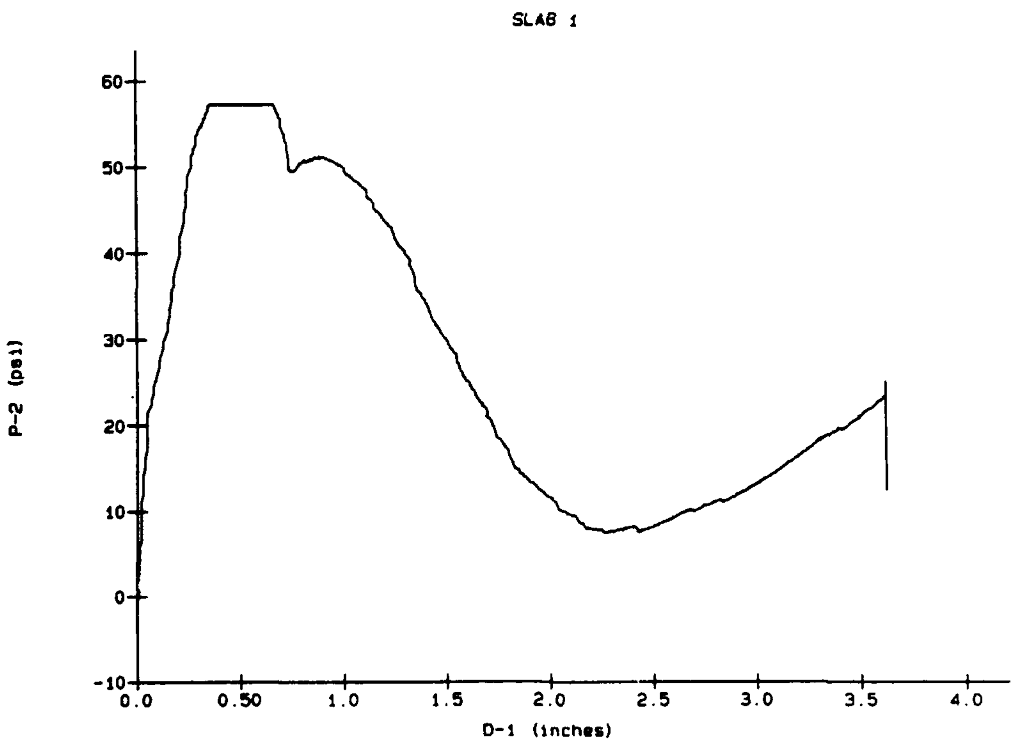
700
800
TIME (seconds)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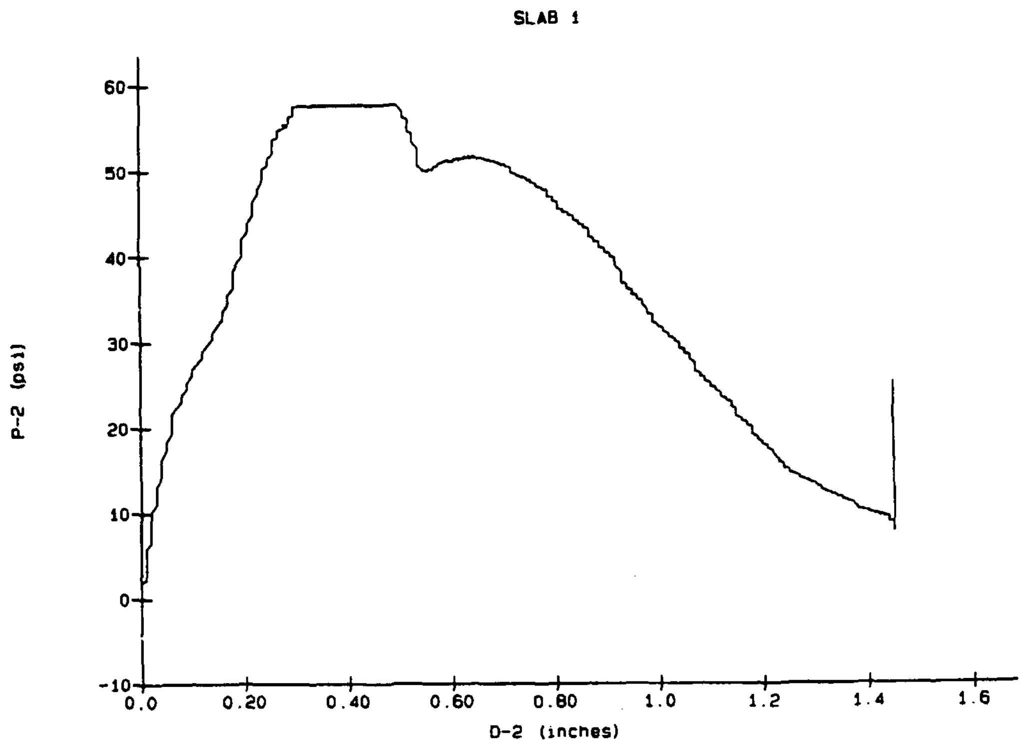
3.0
3.5
4.0
D-1 (inches)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-10
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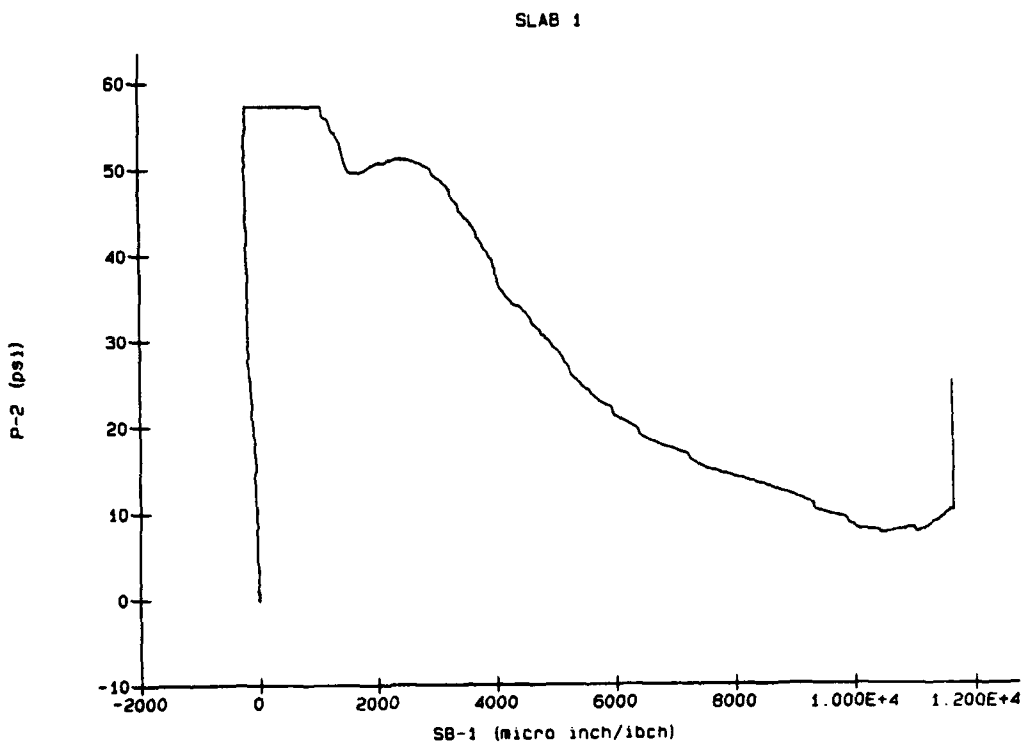
1.2
1.4
1.6
D-2 (inches)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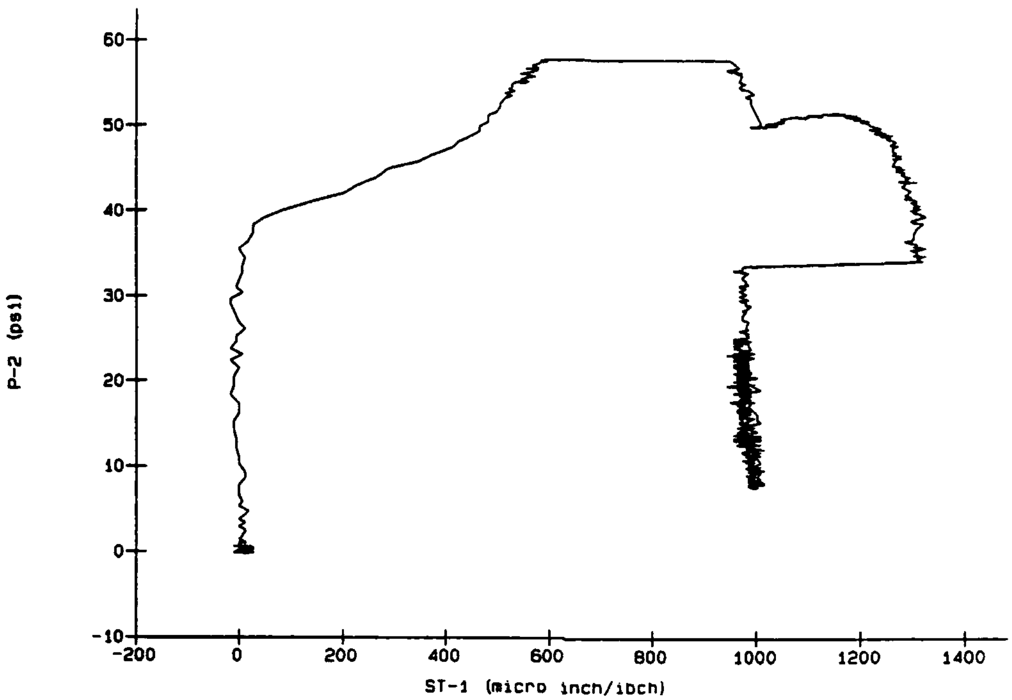
SB-1 (micro inch/ibch)

SLAB 1



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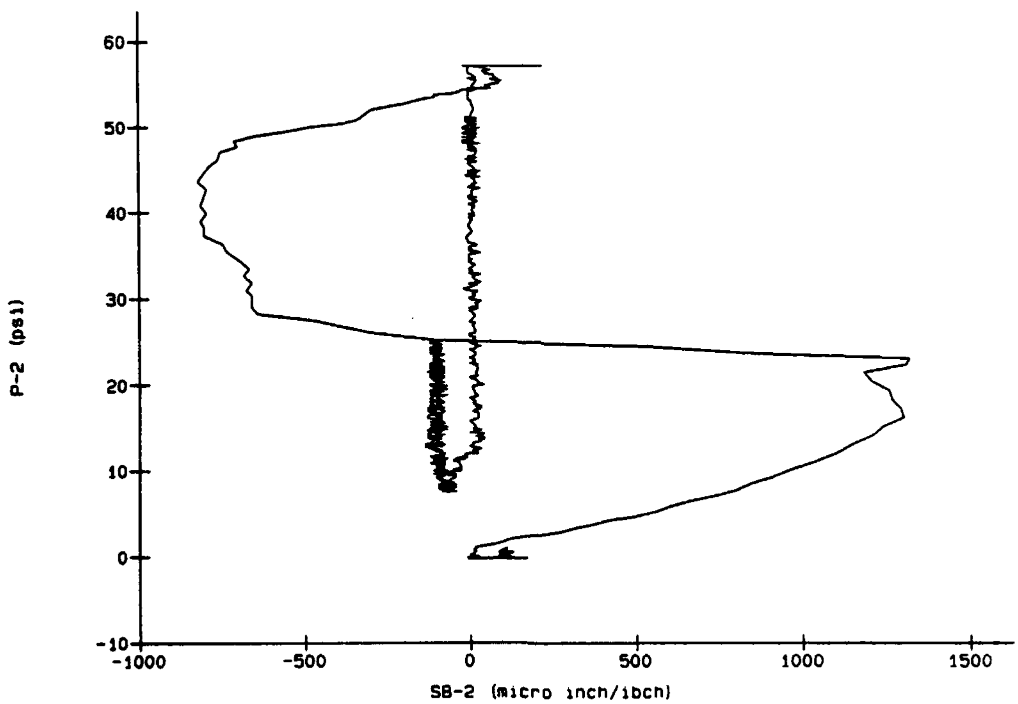
P-2 (psi)
ST-1 (micro inch/inch)

SLAB 1



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1000
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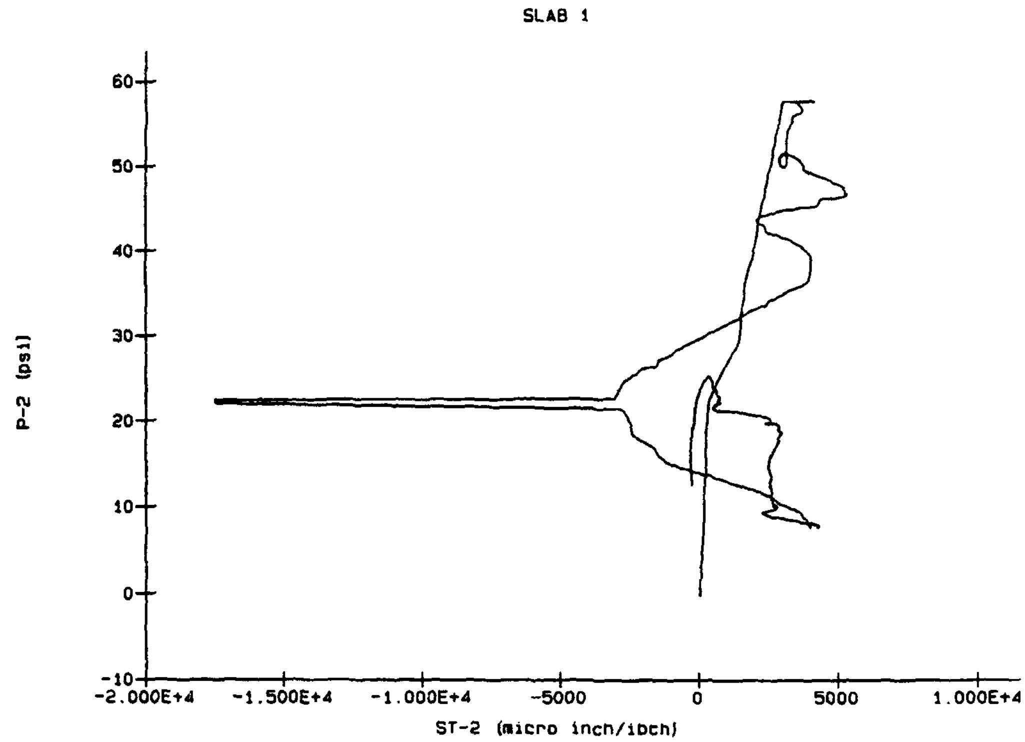
P-2 (psi)
SB-2 (micro inch/inch)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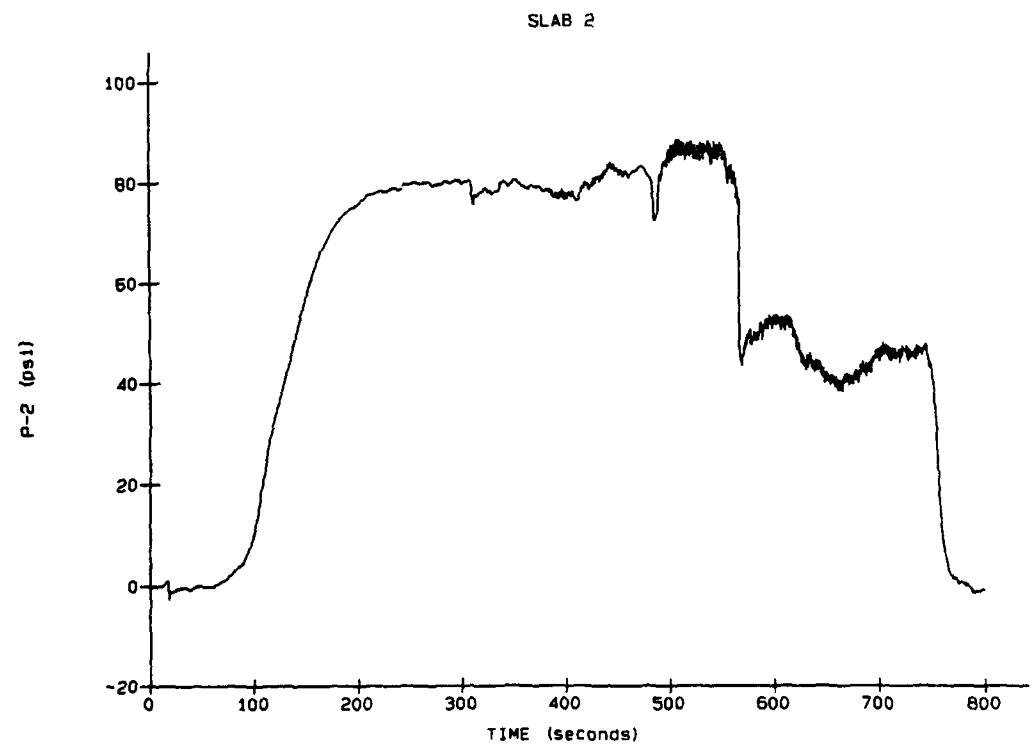
ST-2 (micro inch/inch)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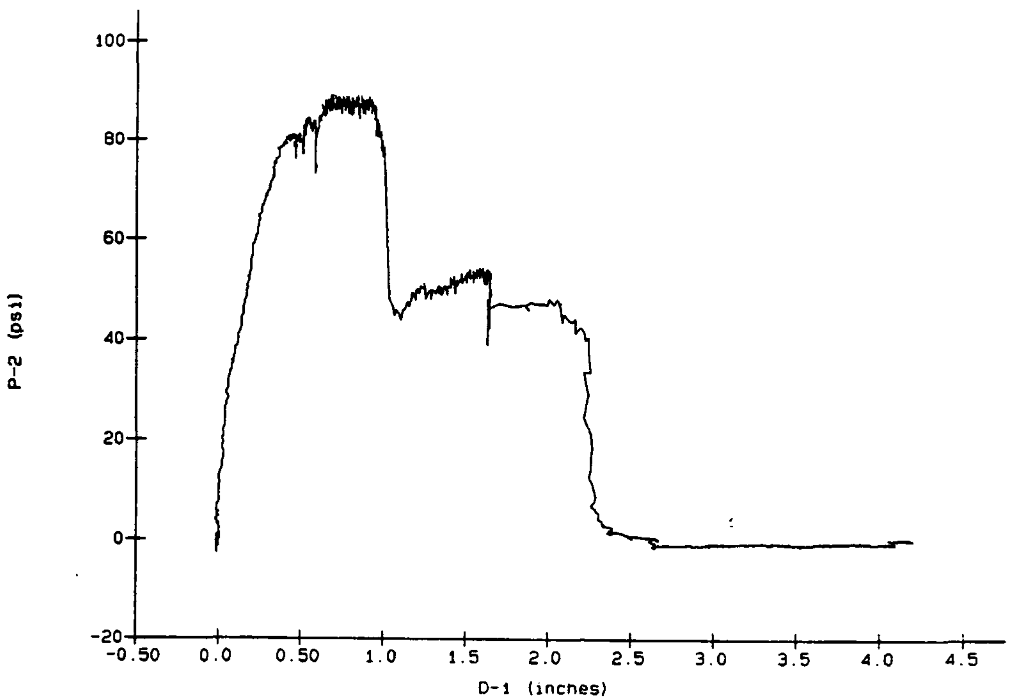

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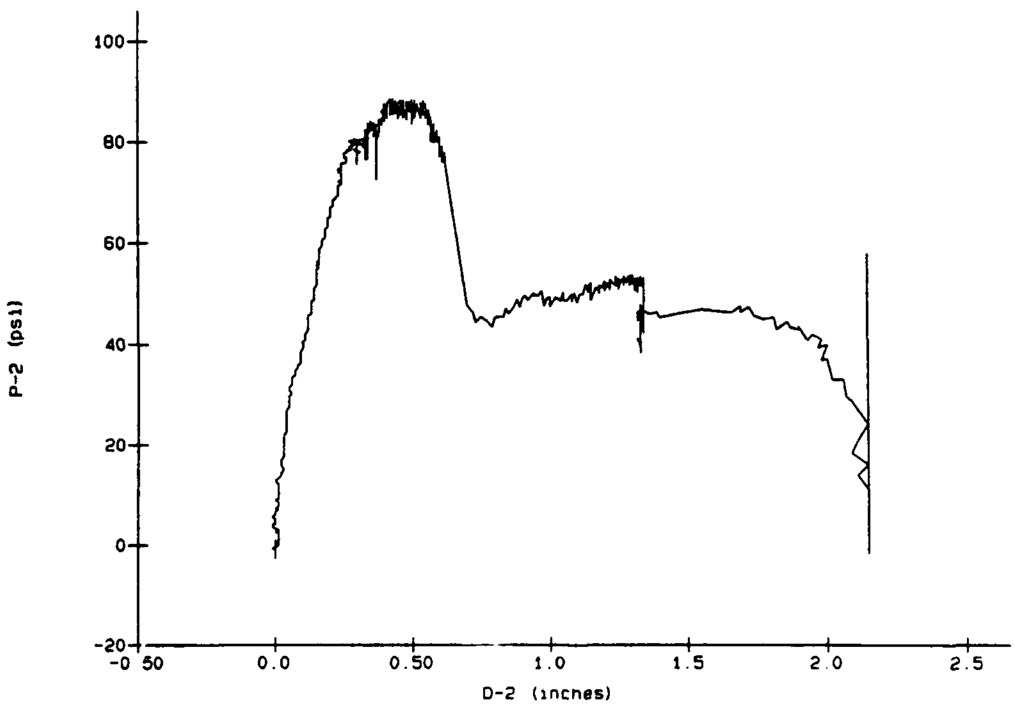

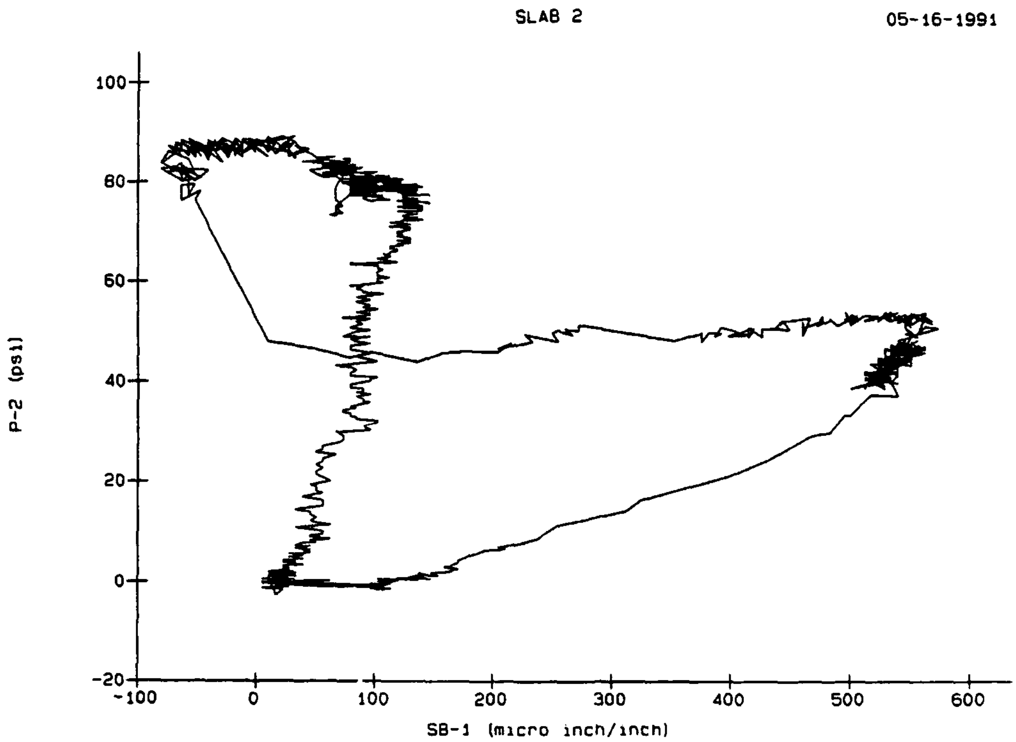

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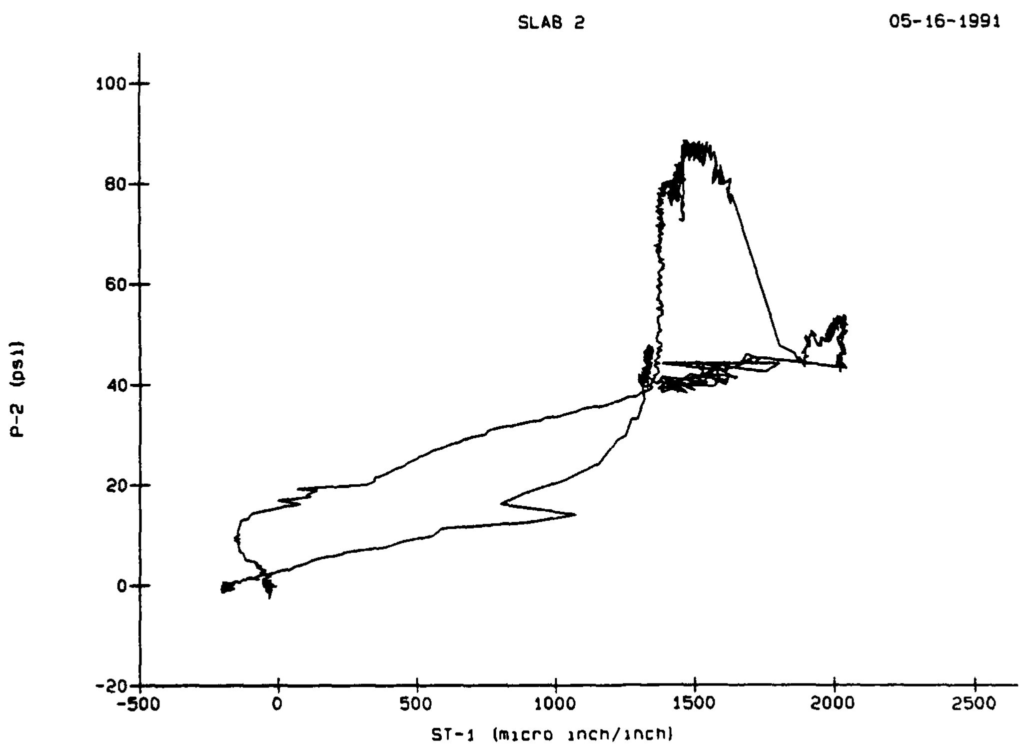
SB-1 (micro inch/inch)



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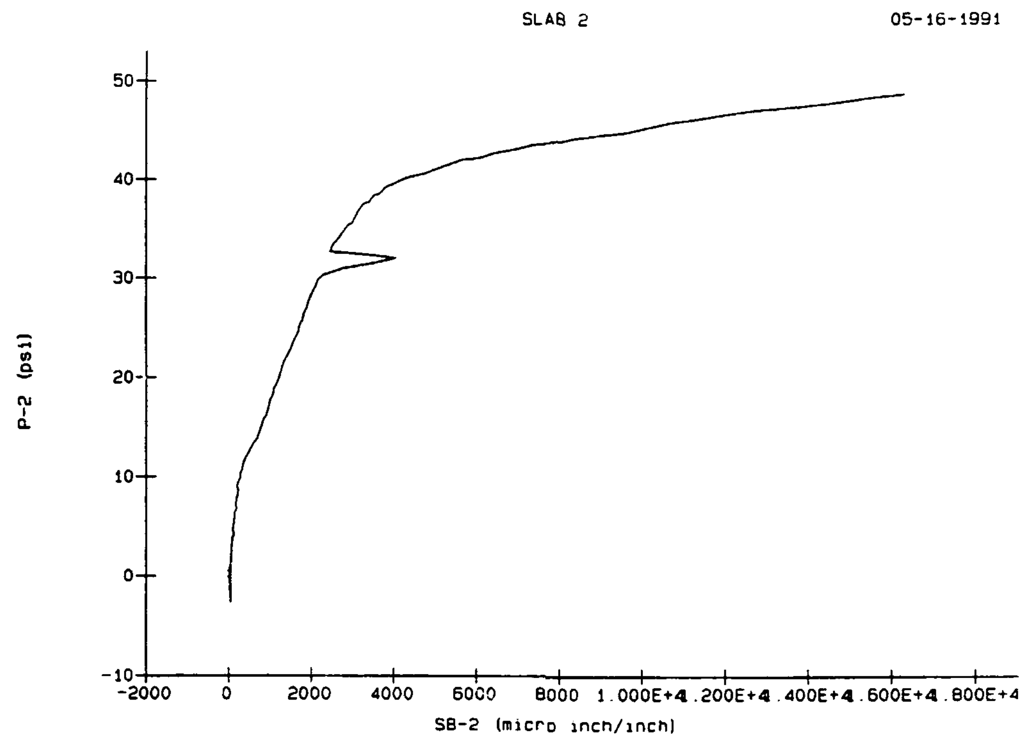

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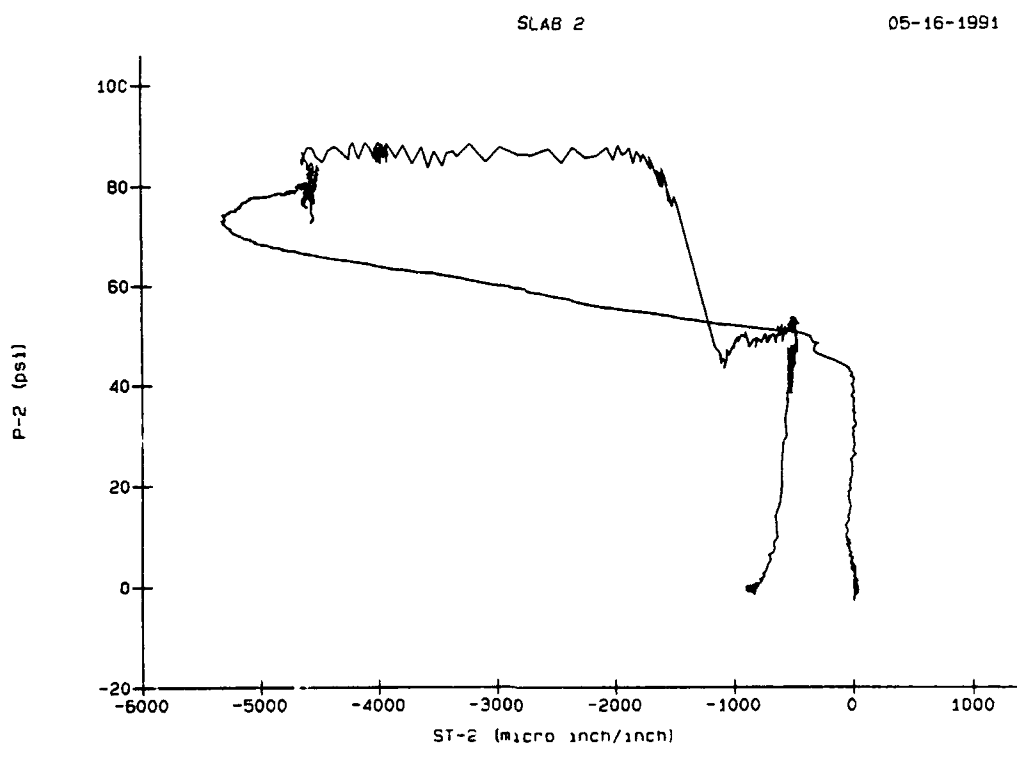

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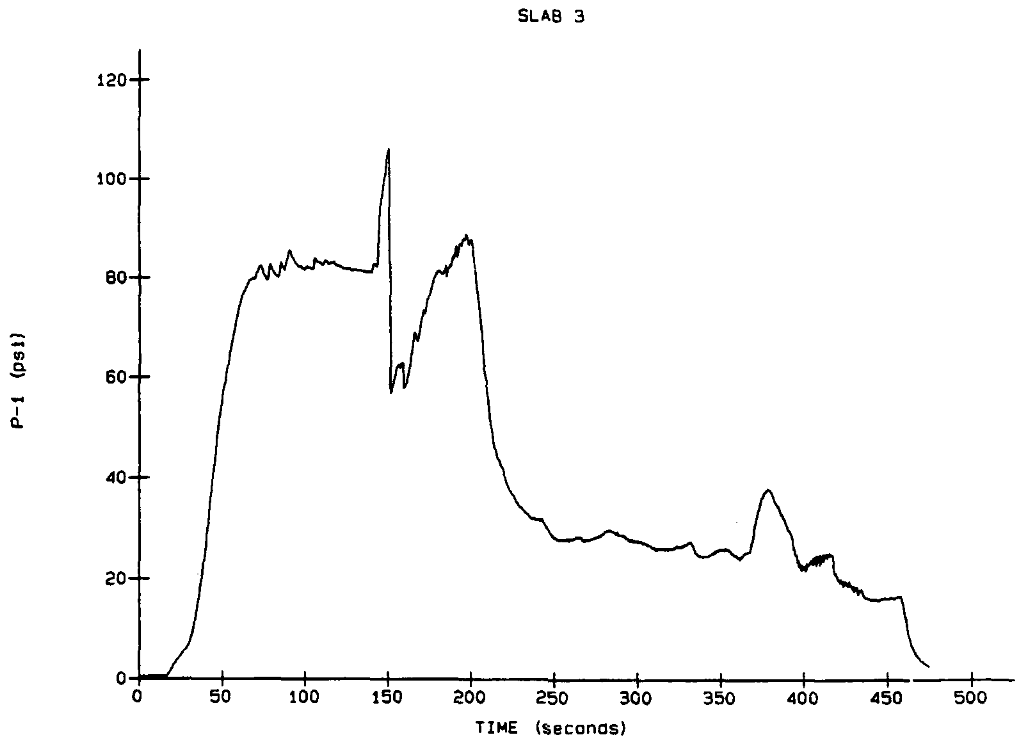

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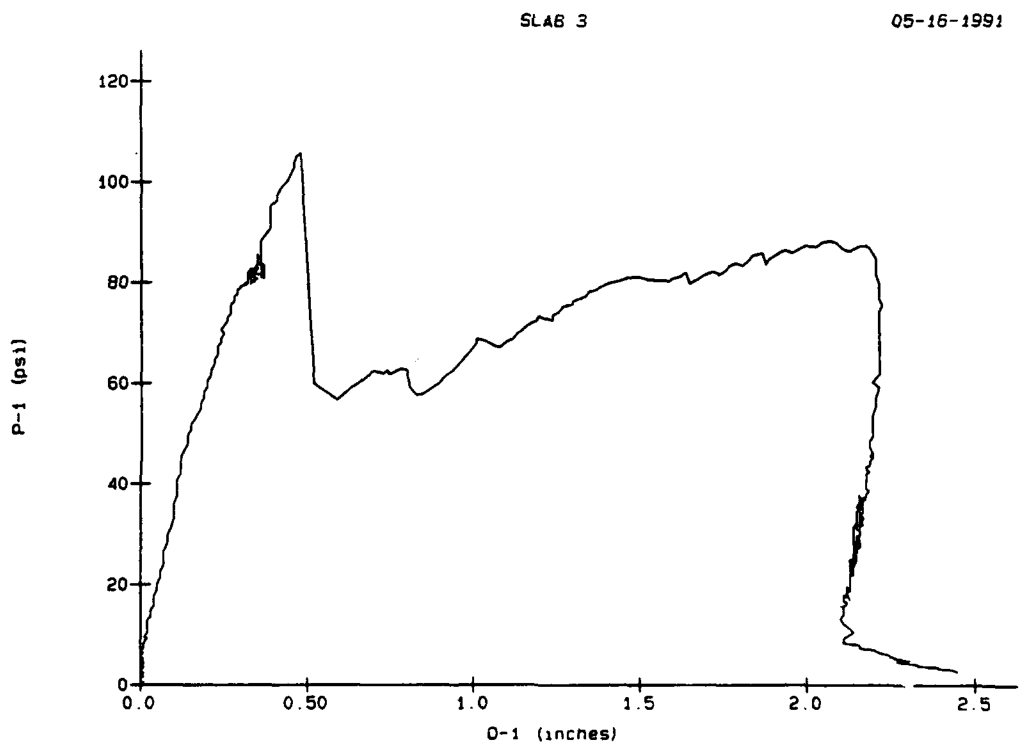
TIME (seconds)



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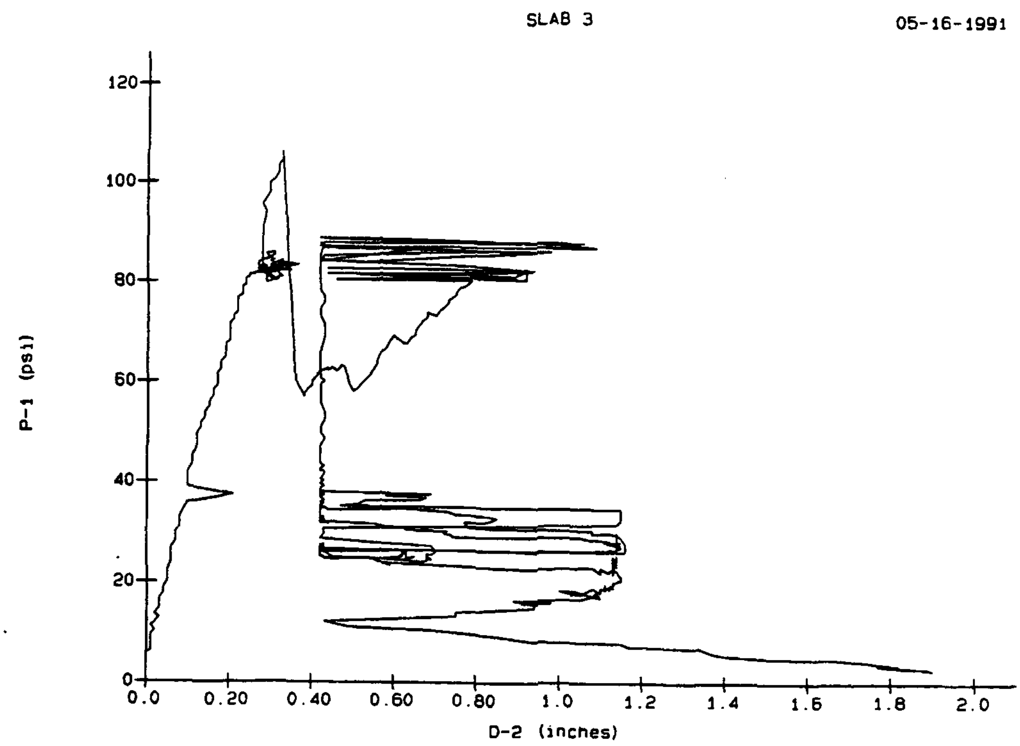
P-1 (psi)
D-1 (inches)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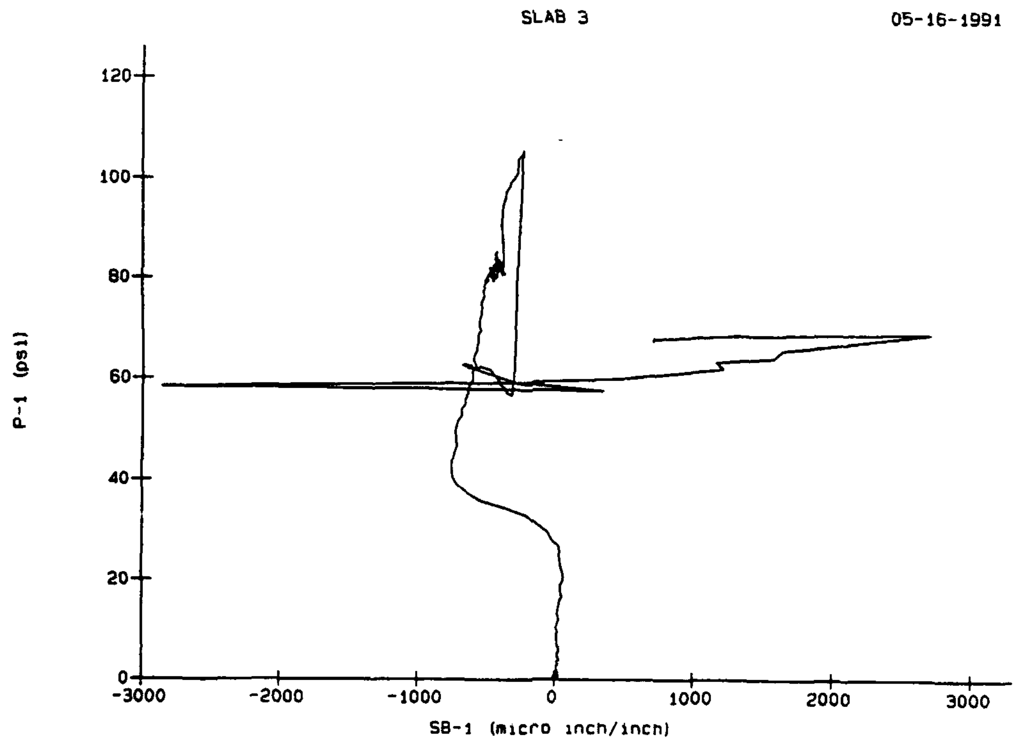
D-2 (inches)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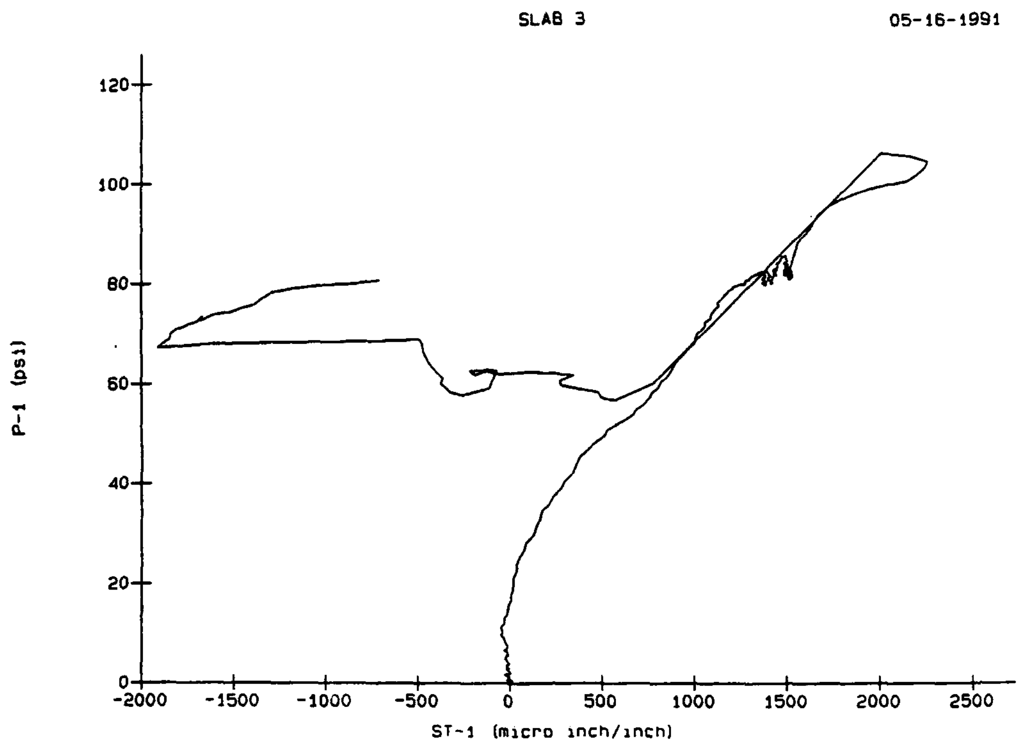
2000
3000
SB-1 (micro inch/inch)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ST-1 (micro inch/inch)
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1000
1500
2000
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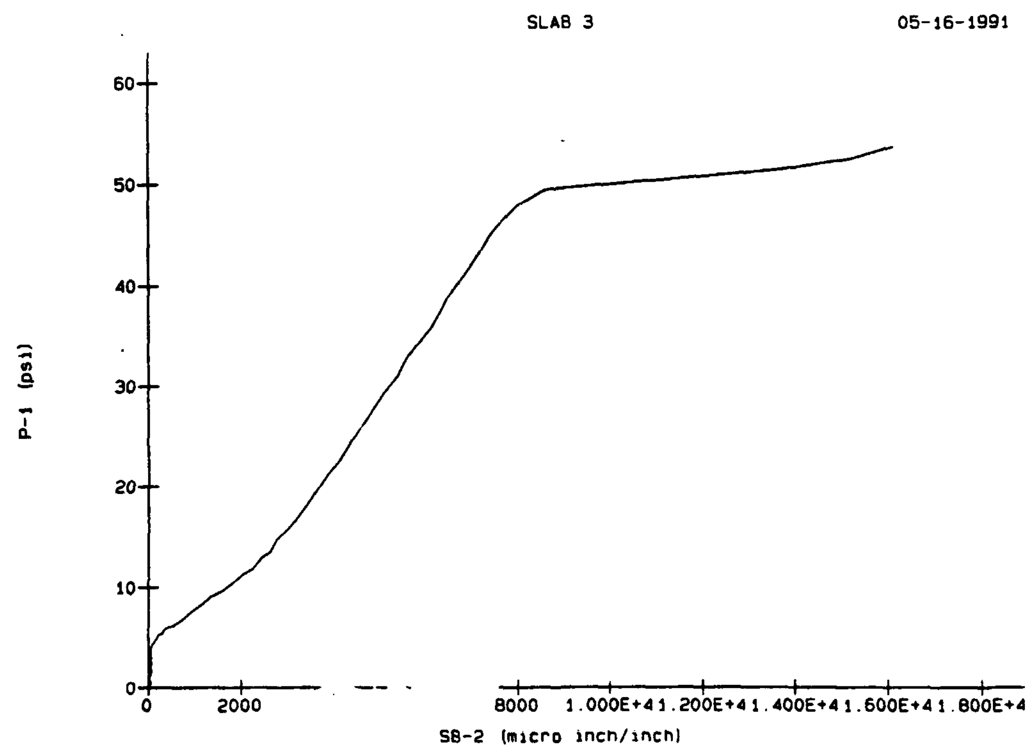
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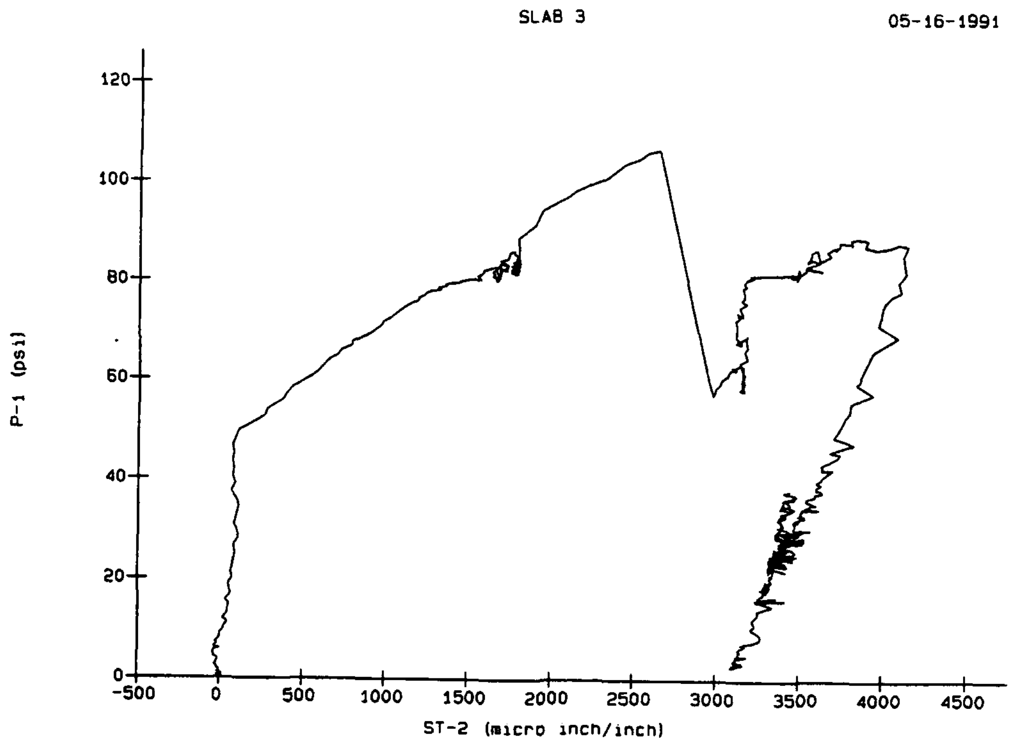
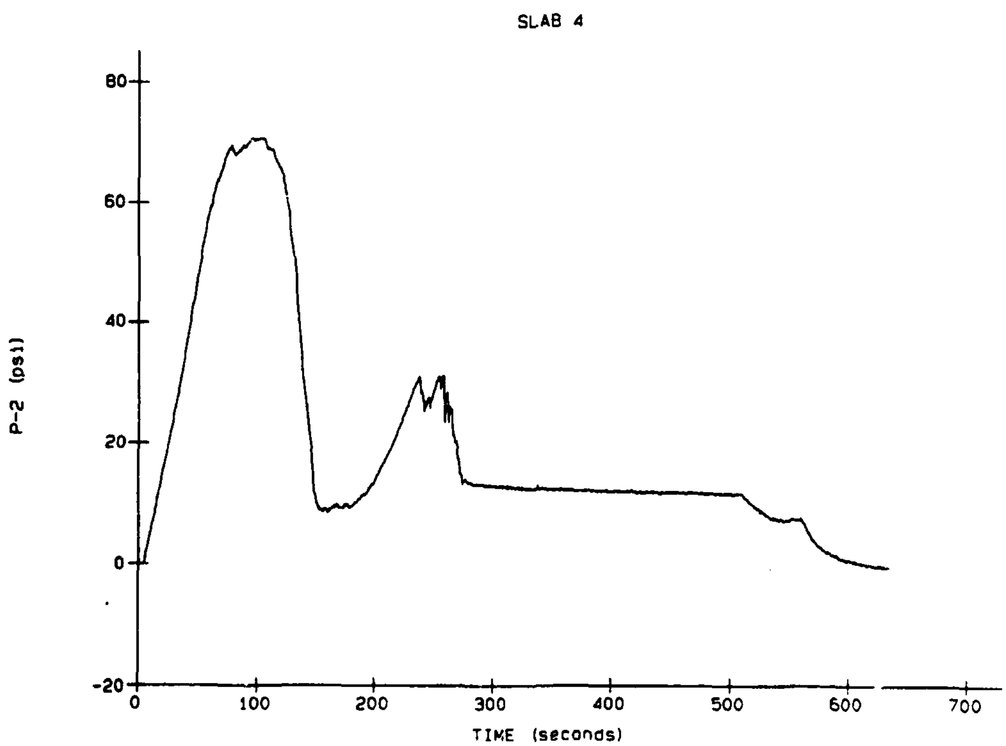
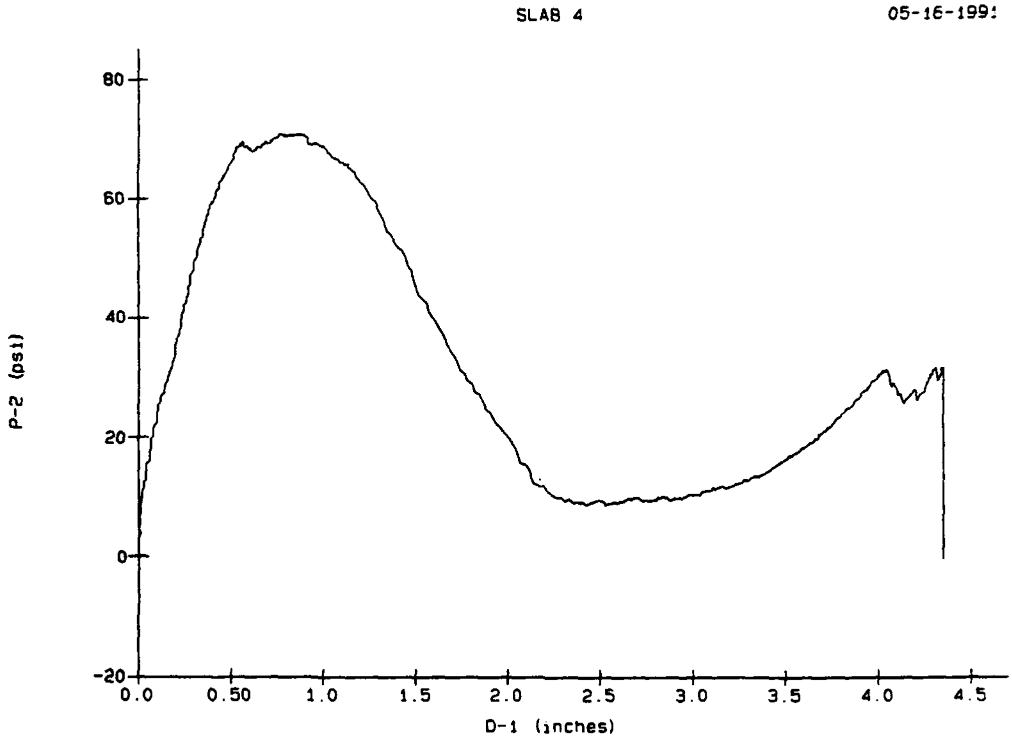
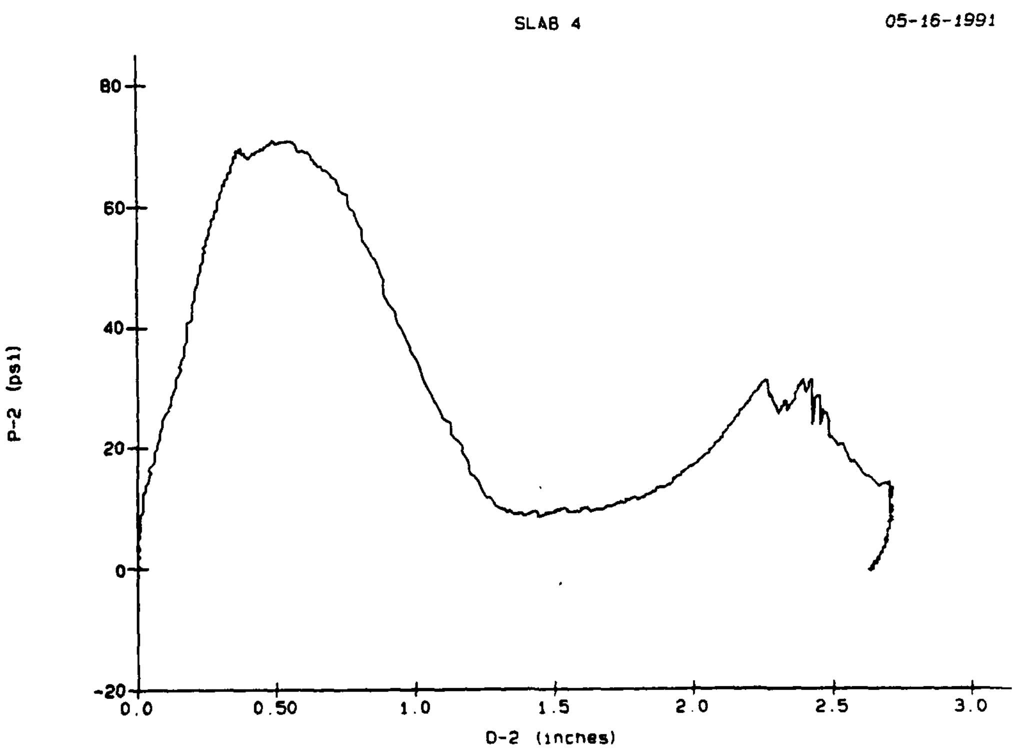
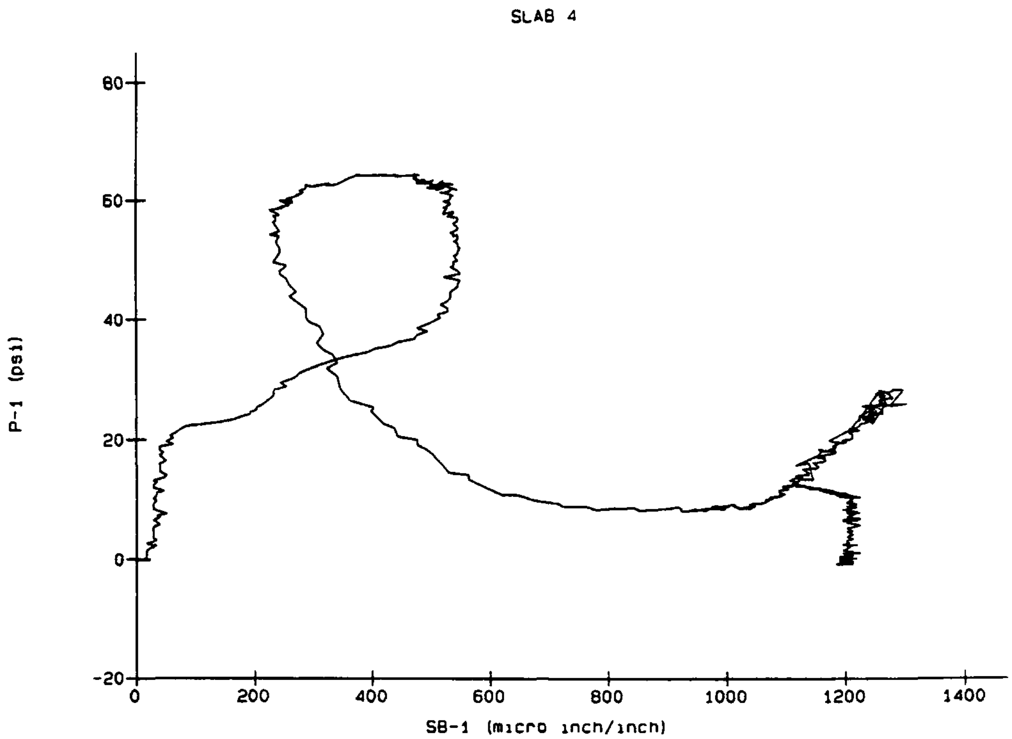
1.600E+4
1.800E+4

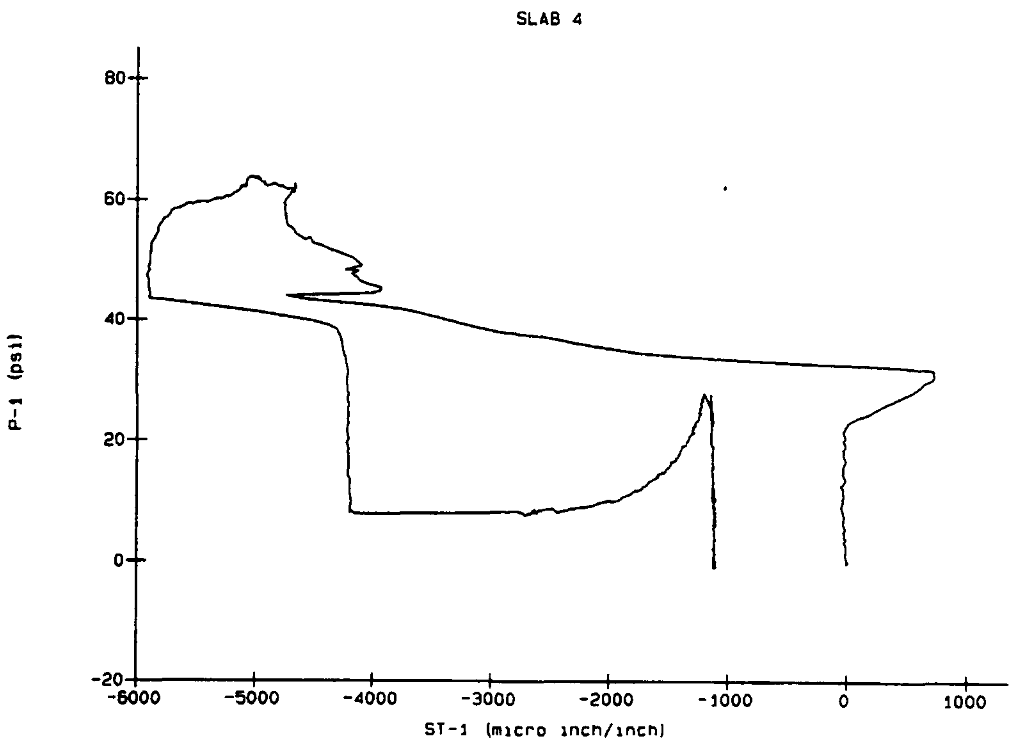

SLAB 3
05-16-1991
P-1 (psi)
120
100
80
60
40
20
0
-500
0
500
1000
1500
2000
2500
3000
3500
4000
4500
ST-2 (micro inch/inch)

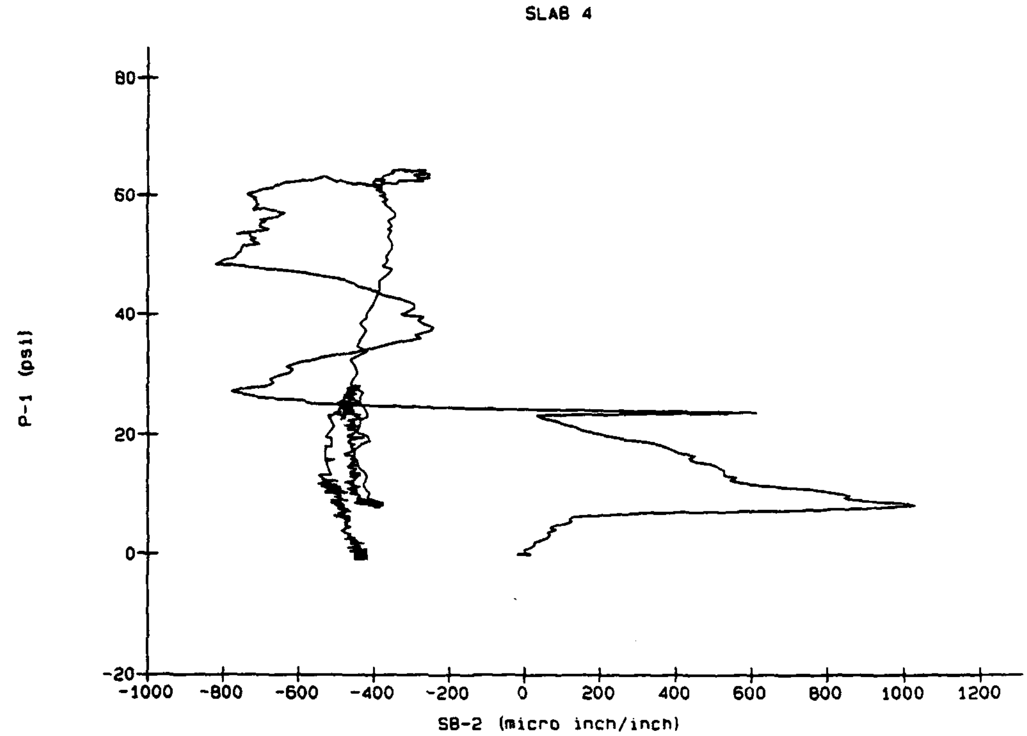

SLAB 4
P-2 (psi)
80
60
40
20
0
-20
0
100
200
300
400
500
600
700
TIME (seconds)

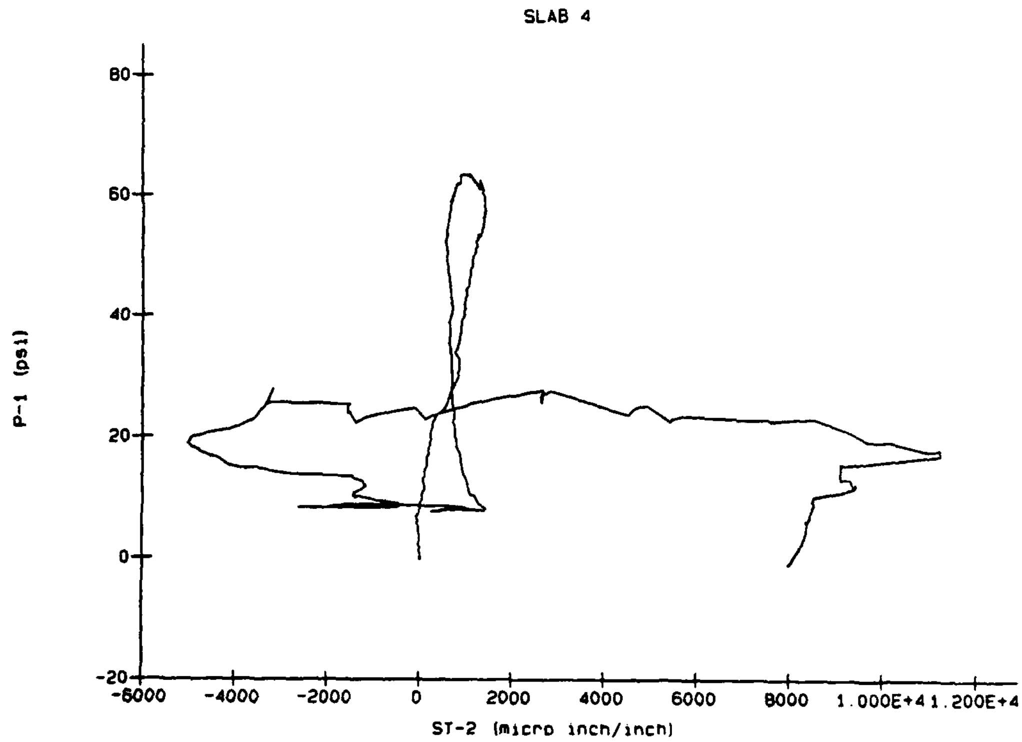

SLAB 4
05-16-1991
P-2 (psi)
D-1 (inches)
80
60
40
20
0
-20
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

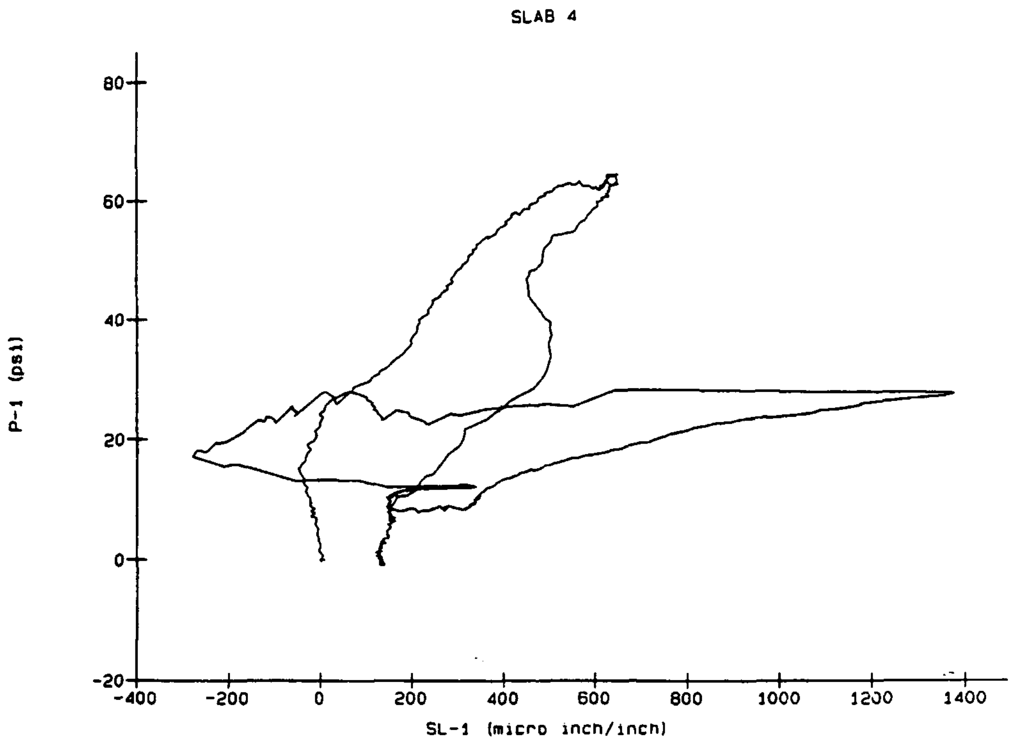

SLAB 4
05-16-1991
P-2 (psi)
D-2 (inches)
80
60
40
20
0
-20
0.0
0.50
1.0
1.5
2.0
2.5
3.0

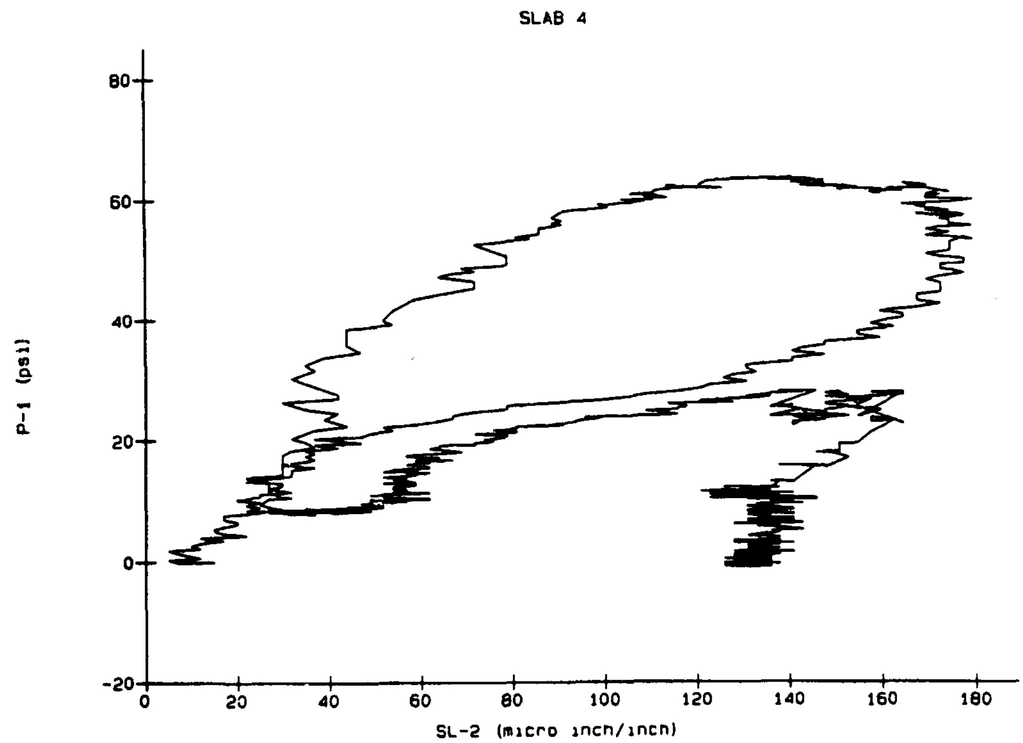

SLAB 4
P-1 (psi)
80
60
40
20
0
-20
0
200
400
600
800
1000
1200
1400
SB-1 (micro inch/inch)

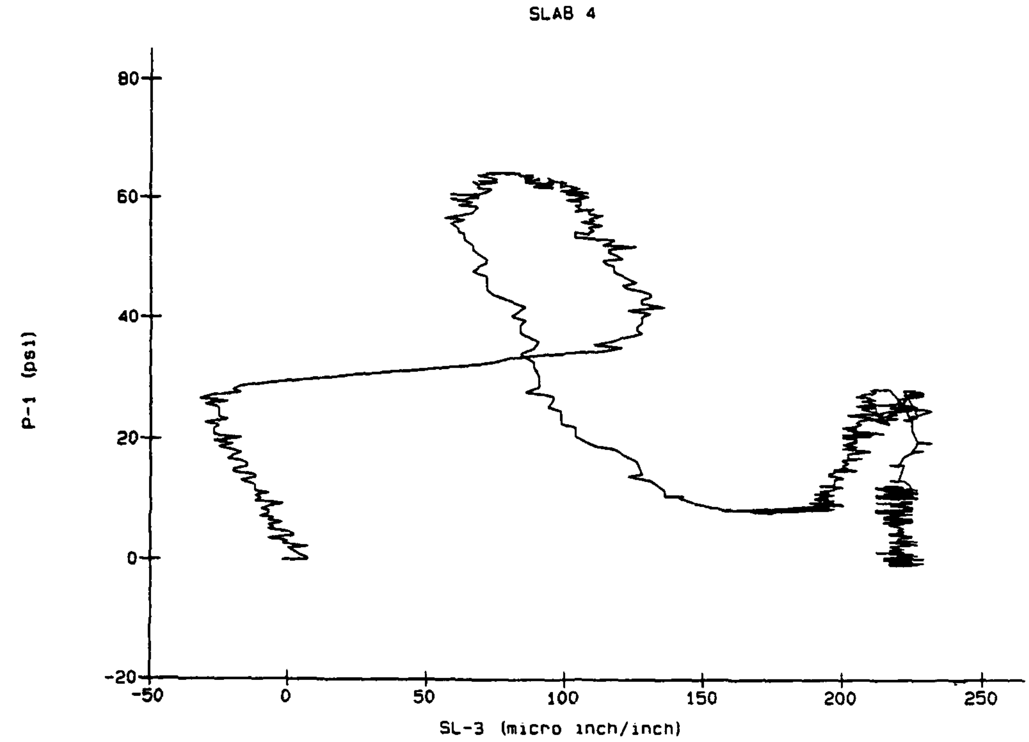

SLAB 4
P-1 (psi)
80
60
40
20
0
-20
-6000
-5000
-4000
-3000
-2000
-1000
0
1000
ST-1 (micro inch/inch)


SLAB 4
80
60
40
20
0
-20
P-1 (psi)
-1000
-800
-600
-400
-200
0
200
400
600
800
1000
1200
SB-2 (micro inch/inch)

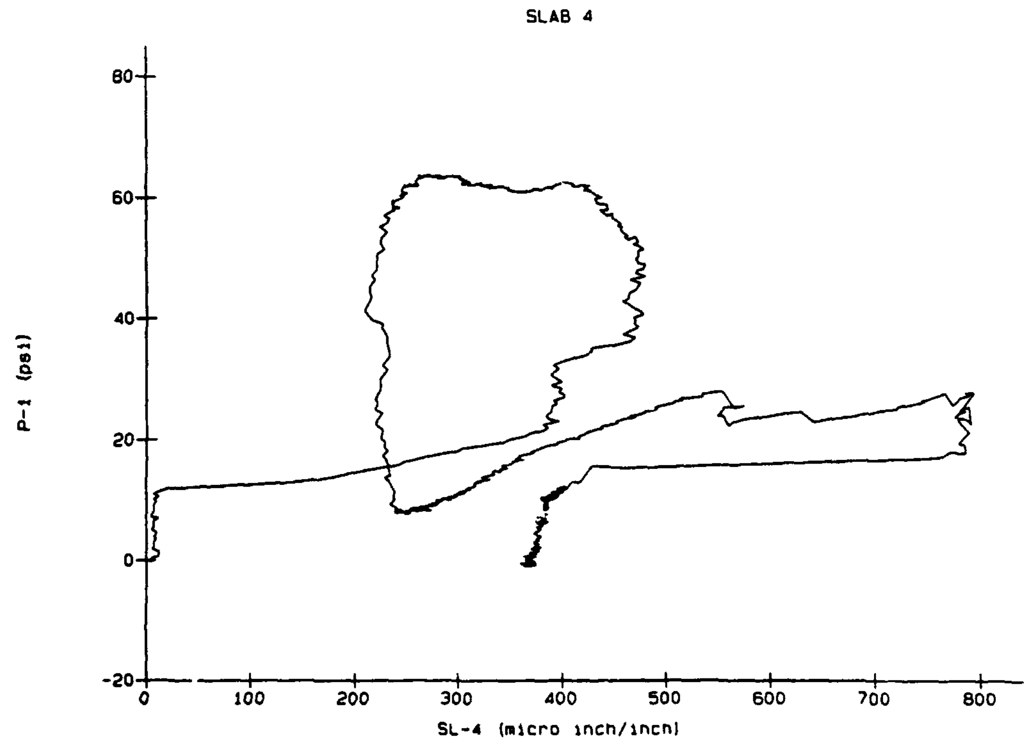

SLAB 4
80
60
40
20
0
-20
P-1 (psi)
-6000
-4000
-2000
0
2000
4000
6000
8000
1.000E+4
1.200E+4
ST-2 (micro inch/inch)


SLAB 4
P-1 (psi)
SL-1 (micro inch/inch)


SLAB 4
P-1 (psi)
SL-2 (micro inch/inch)

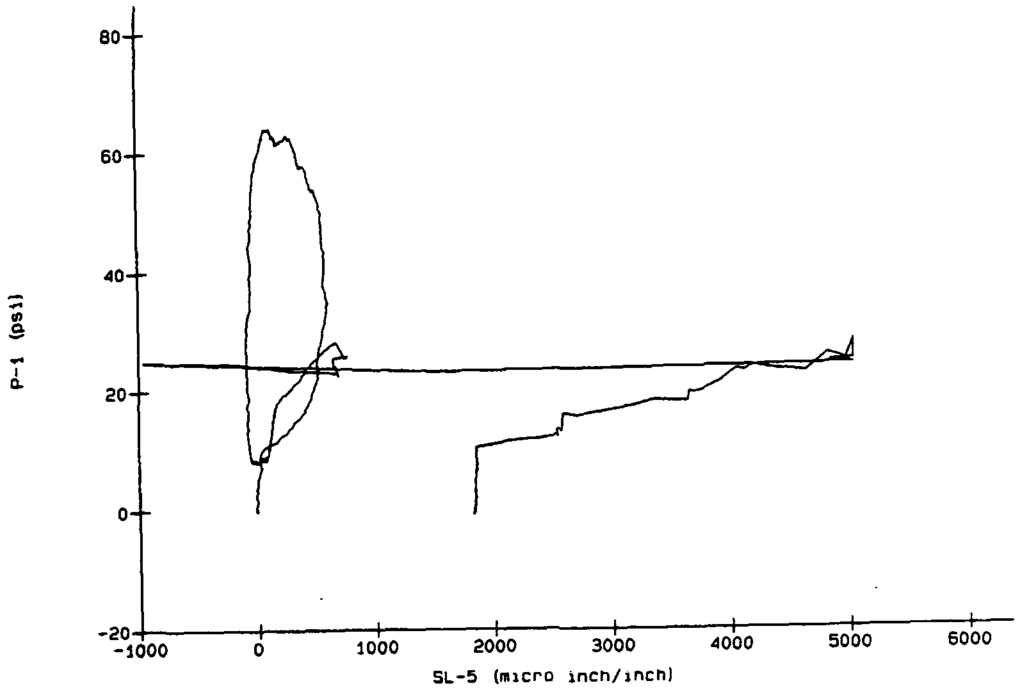


SLAB 4
P-1 (psi)
80
60
40
20
0
-20
-50
0
50
100
150
200
250
SL-3 (micro inch/inch)

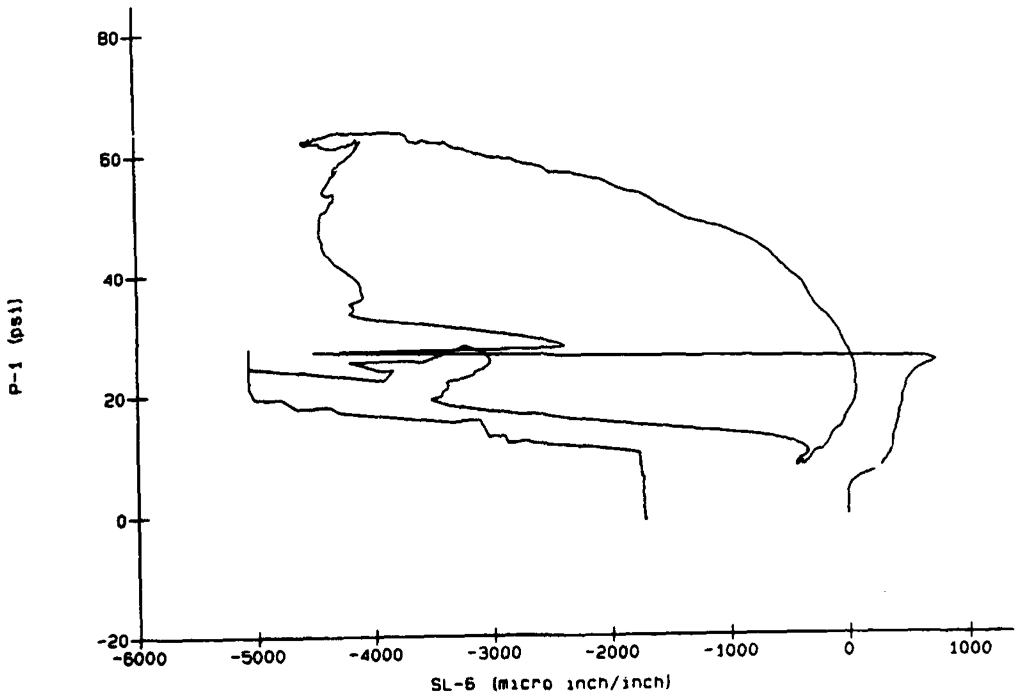


SLAB 4
P-1 (psi)
80
60
40
20
0
-20
0
100
200
300
400
500
600
700
800
SL-4 (micro inch/inch)

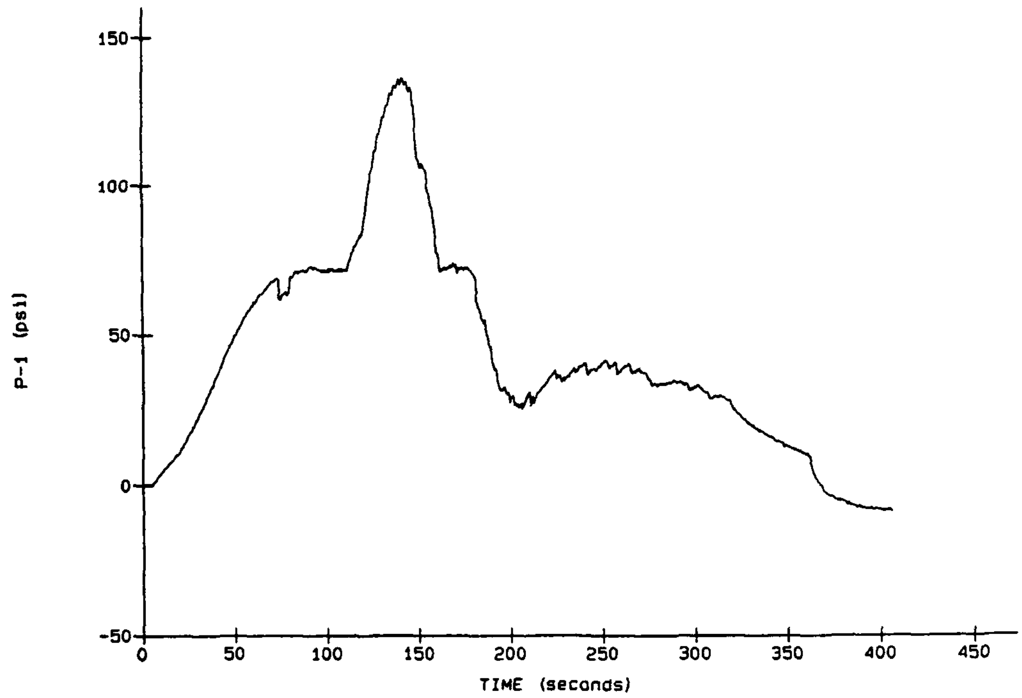
SLAB 4


80
60
40
20
0
-20
P-1 (psi)
-1000
0
1000
2000
3000
4000
5000
6000
SL-5 (micro inch/inch)

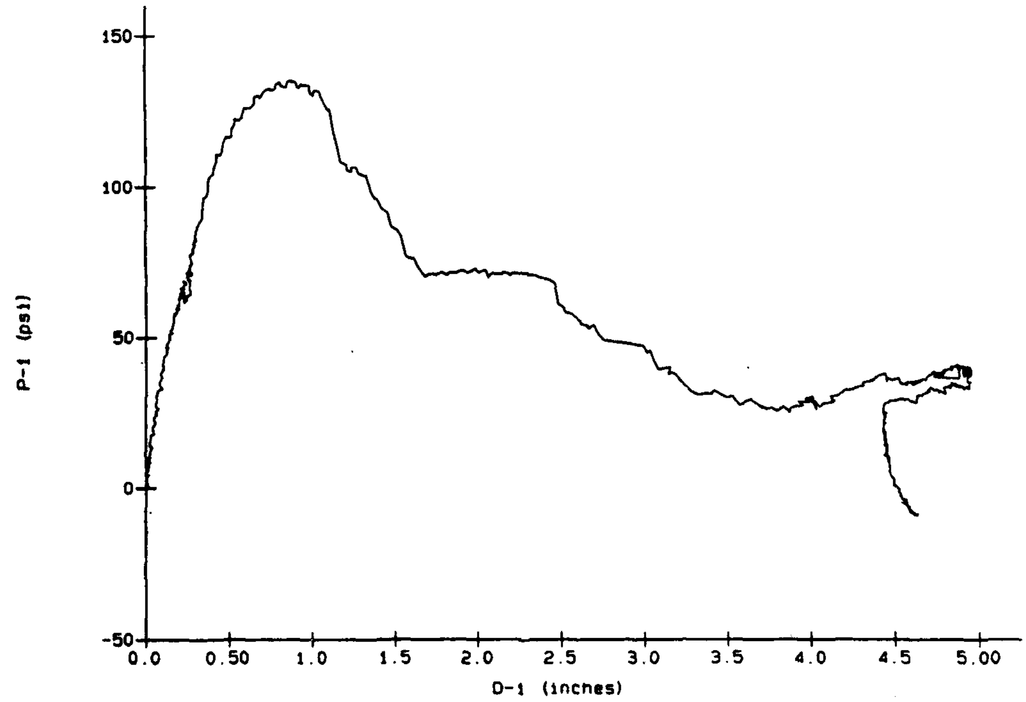
SLAB 4

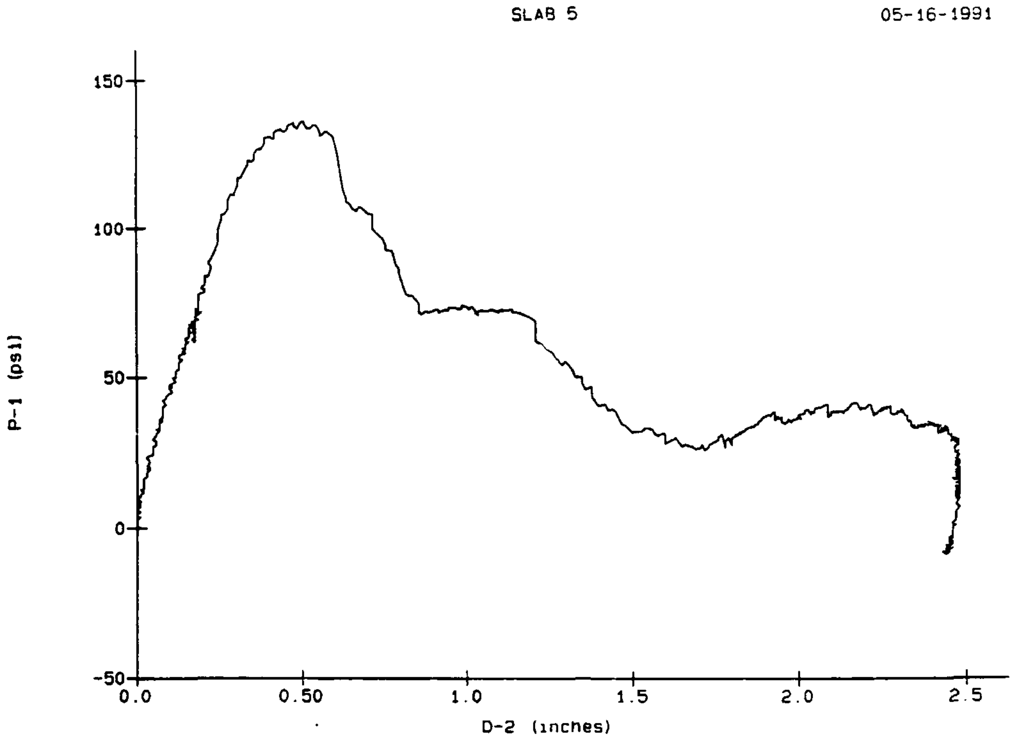

80
60
40
20
0
-20
P-1 (psi)
-6000
-5000
-4000
-3000
-2000
-1000
0
1000
SL-6 (micro inch/inch)

SLAB 5

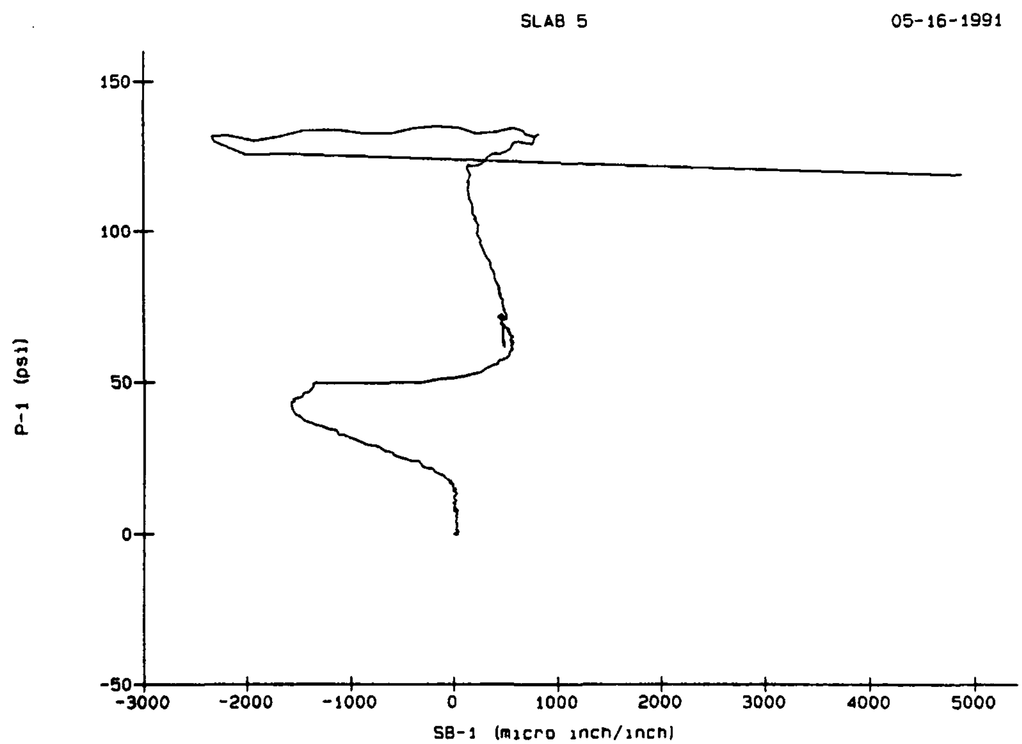


SLAB 5 05-16-1991

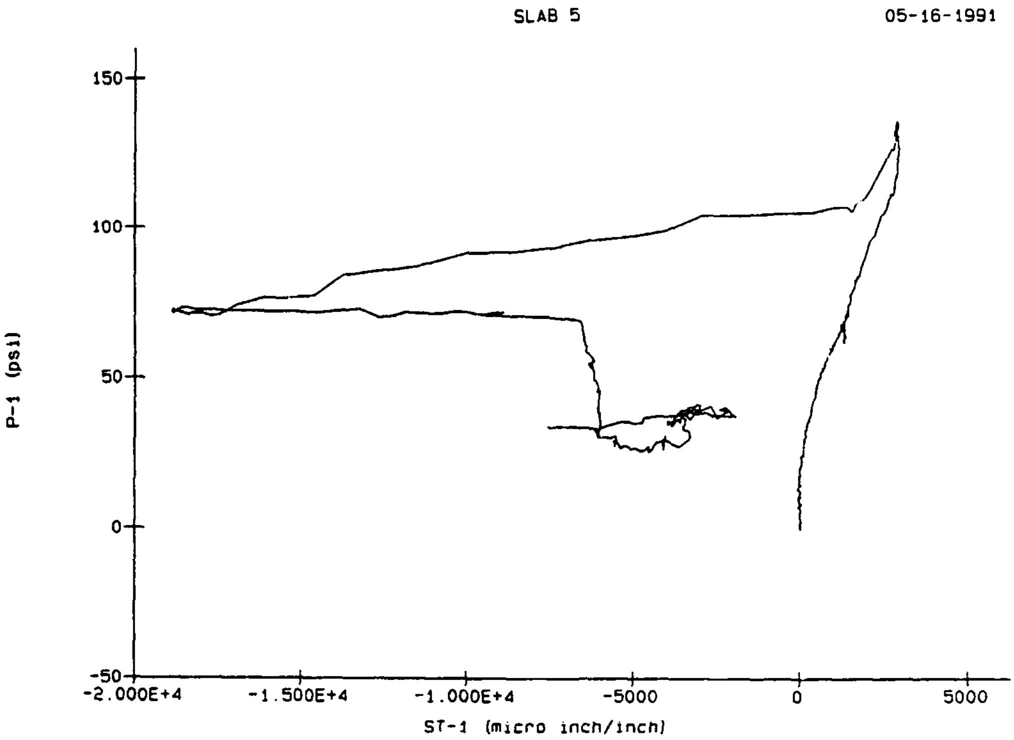


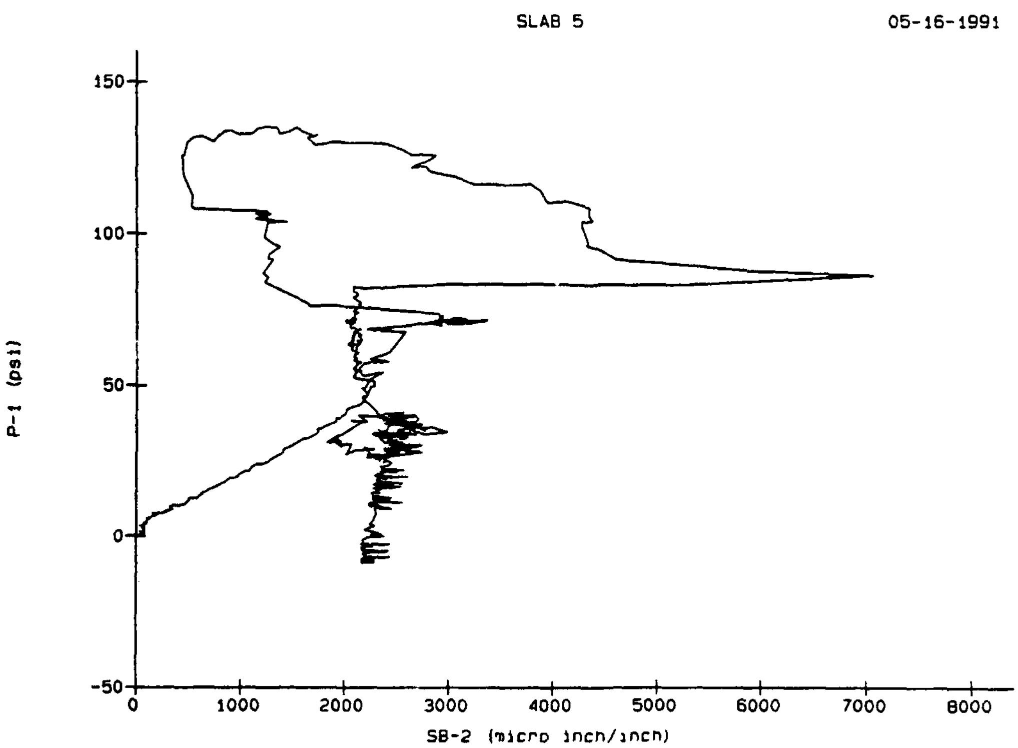


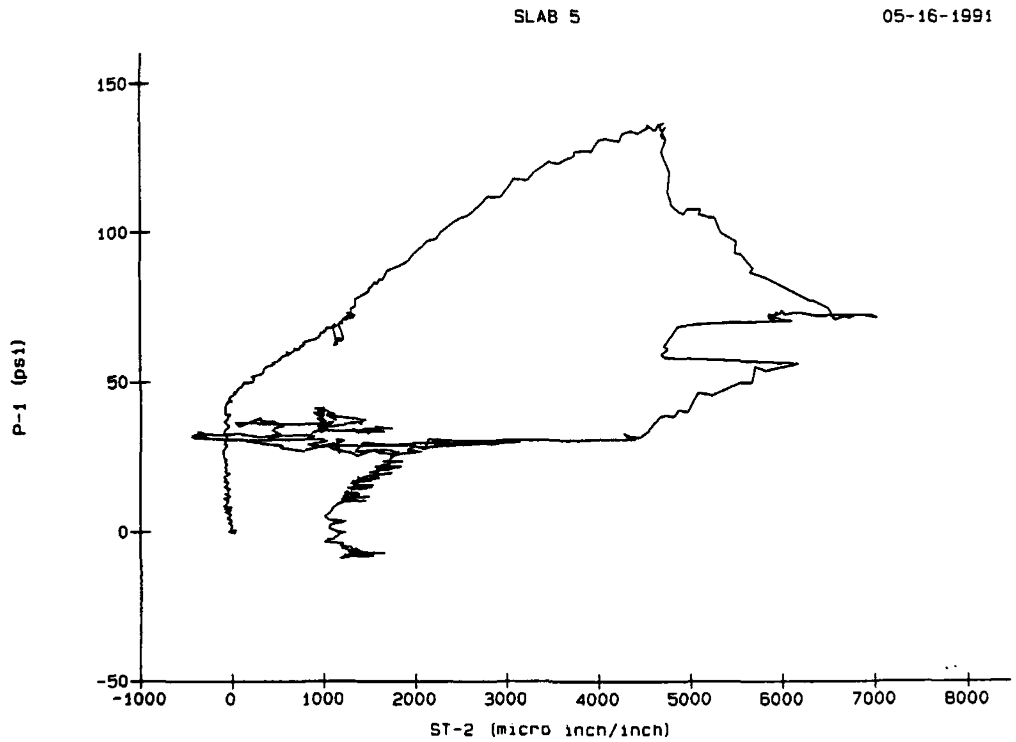
SLAB 5
05-16-1991
150
100
50
0
-50
P-1 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
D-2 (inches)



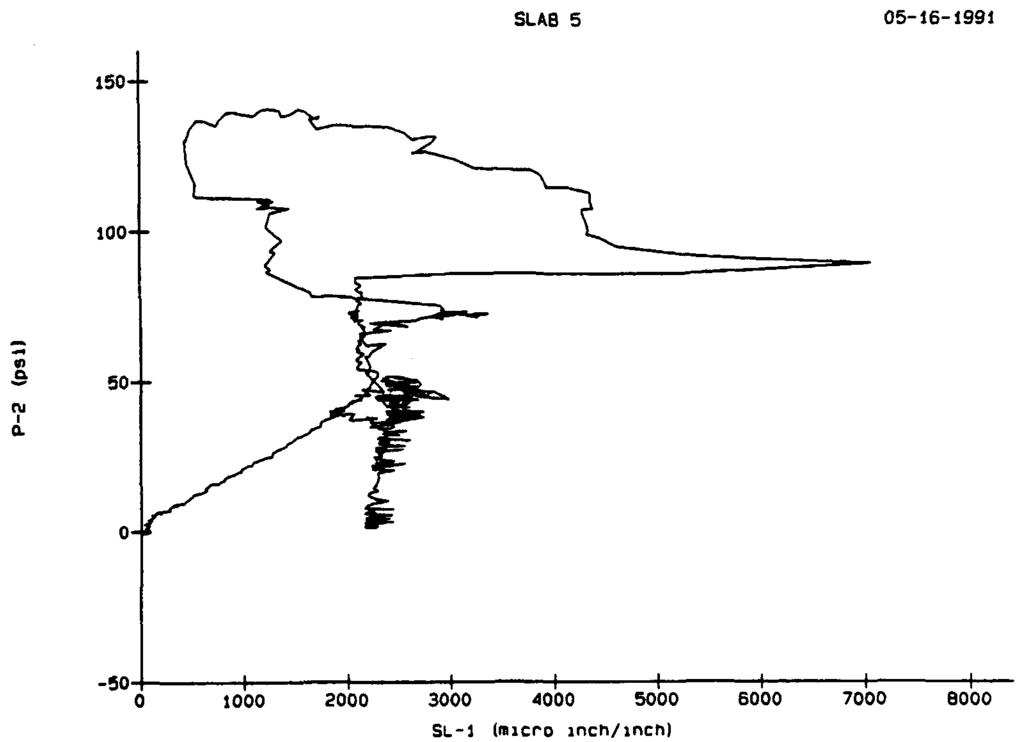
SLAB 5
05-16-1991
150
100
50
0
-50
P-1 (psi)
-3000
-2000
-1000
0
1000
2000
3000
4000
5000
SB-1 (micro inch/inch)


SLAB 5
05-16-1991
150
100
50
0
-50
-2.000E+4
-1.500E+4
-1.000E+4
-5000
0
5000
P-1 (psi)
ST-1 (micro inch/inch)

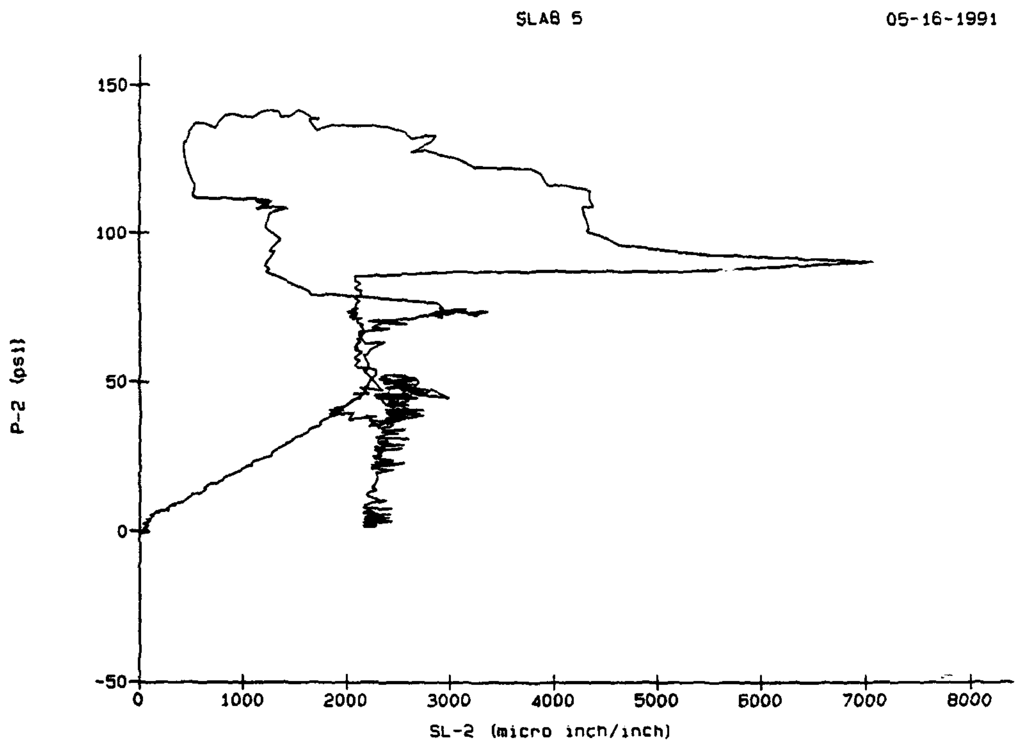

SLAB 5
05-16-1991
150
100
50
0
-50
0
1000
2000
3000
4000
5000
6000
7000
8000
P-1 (psi)
SB-2 (micro inch/inch)

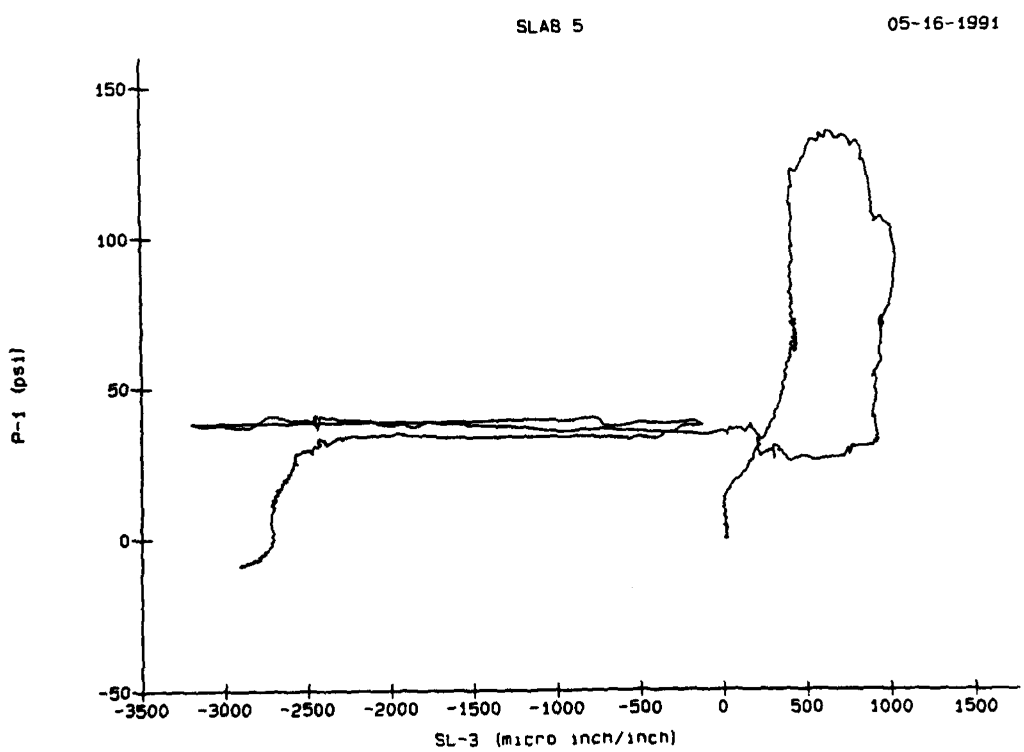


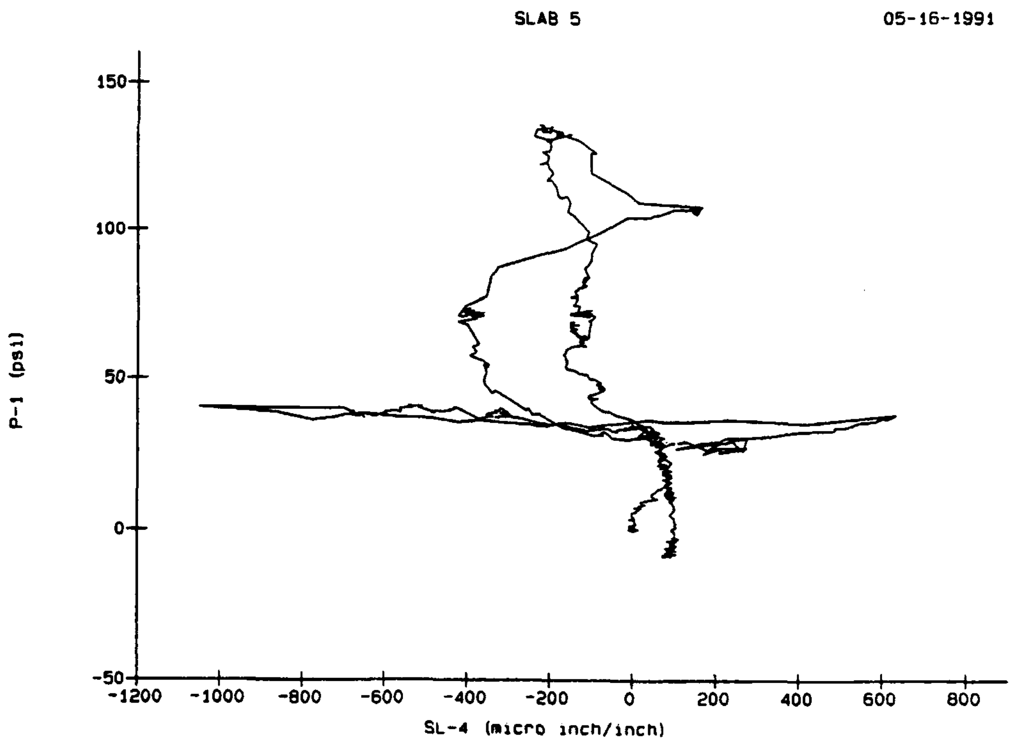
SLAB 5
05-16-1991
150
100
50
0
-50
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
P-1 (psi)
ST-2 (micro inch/inch)



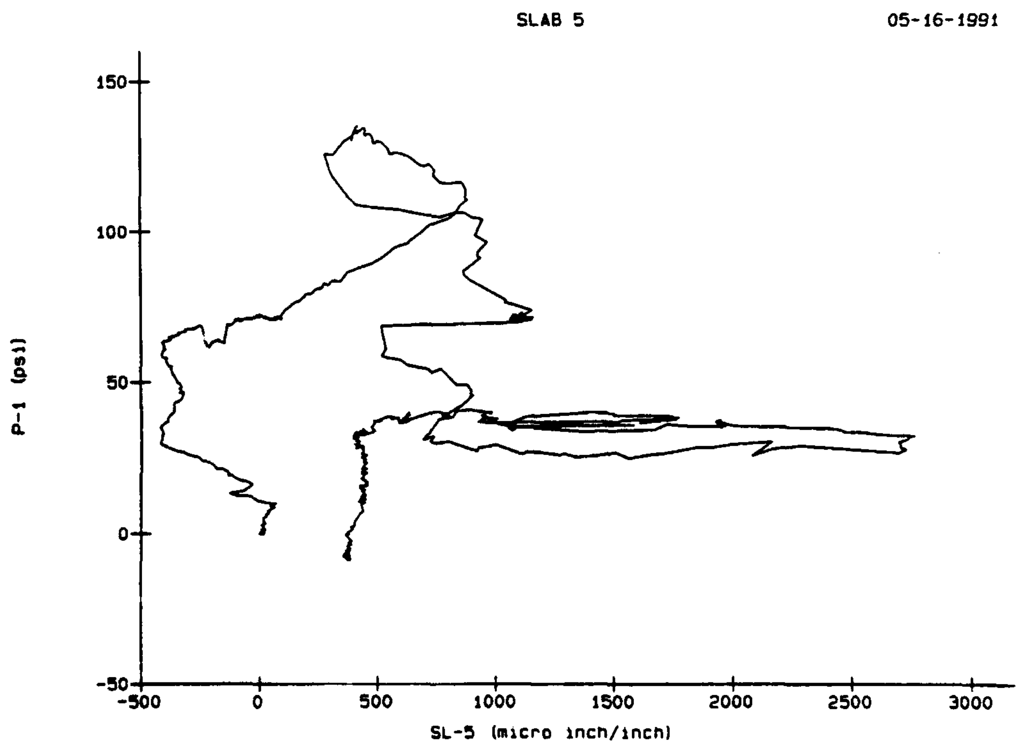
SLAB 5
05-16-1991
150
100
50
0
-50
0
1000
2000
3000
4000
5000
6000
7000
8000
P-2 (psi)
SL-1 (micro inch/inch)


SLAB 5
05-16-1991
150
100
50
0
-50
0
1000
2000
3000
4000
5000
6000
7000
8000
P-2 (psi)
SL-2 (micro inch/inch)

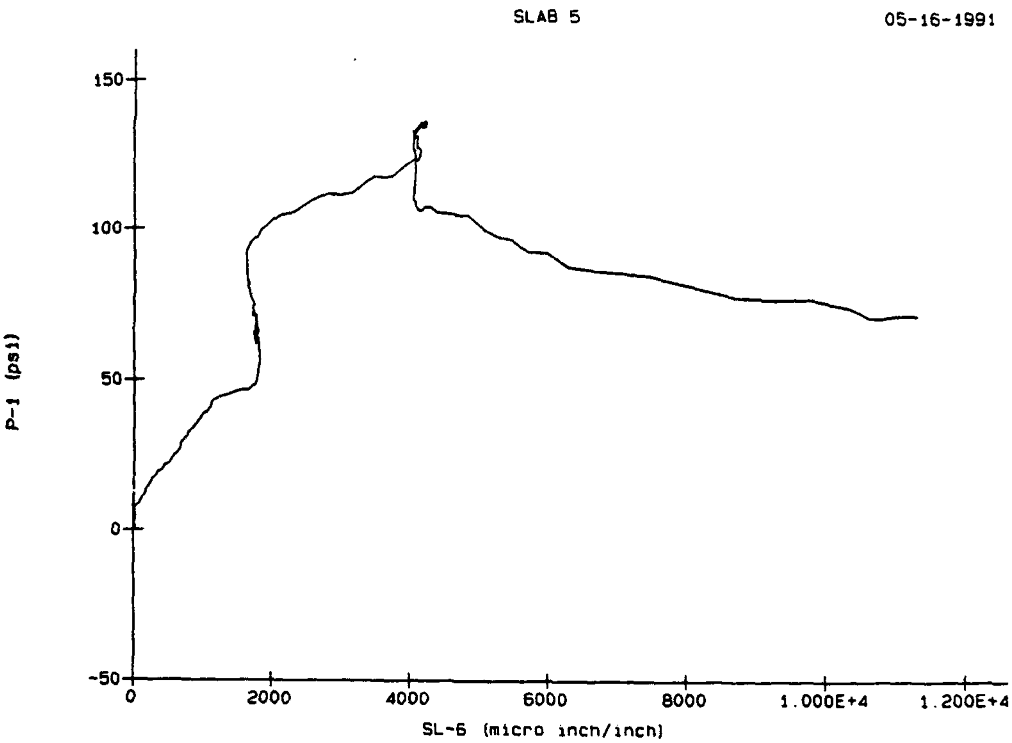

SLAB 5
05-16-1991
150
100
50
0
-50
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
P-1 (psi)
SL-3 (micro inch/inch)

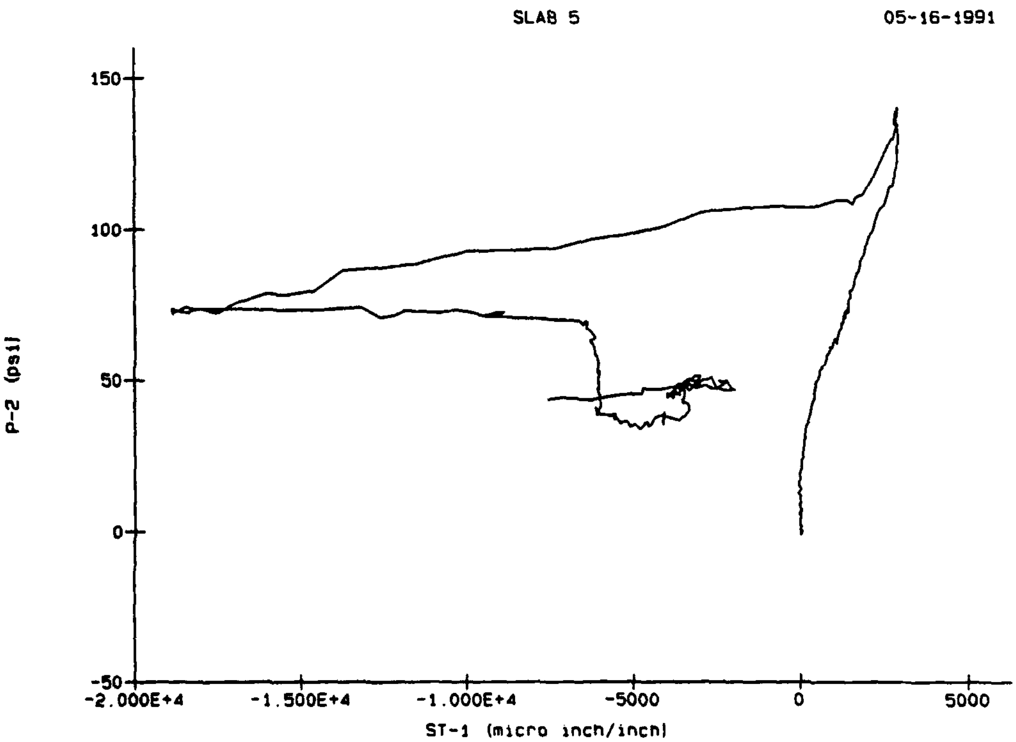


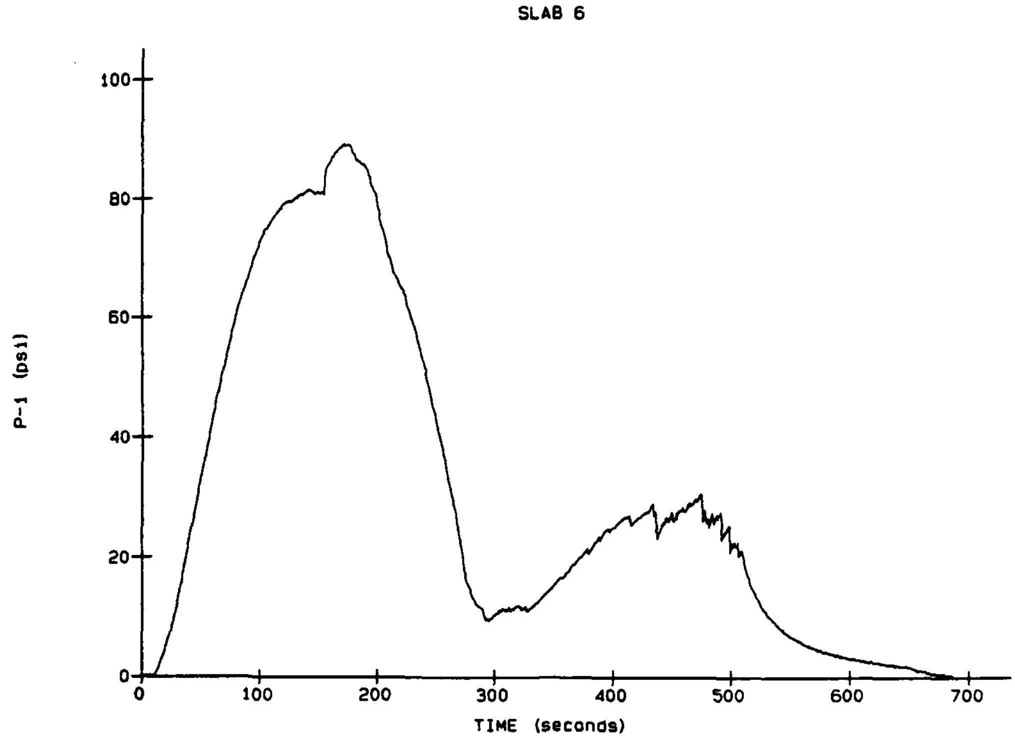
SLAB 5
05-16-1991
150
100
50
0
-50
-1200
-1000
-800
-600
-400
-200
0
200
400
600
800
SL-4 (micro inch/inch)
P-1 (psi)

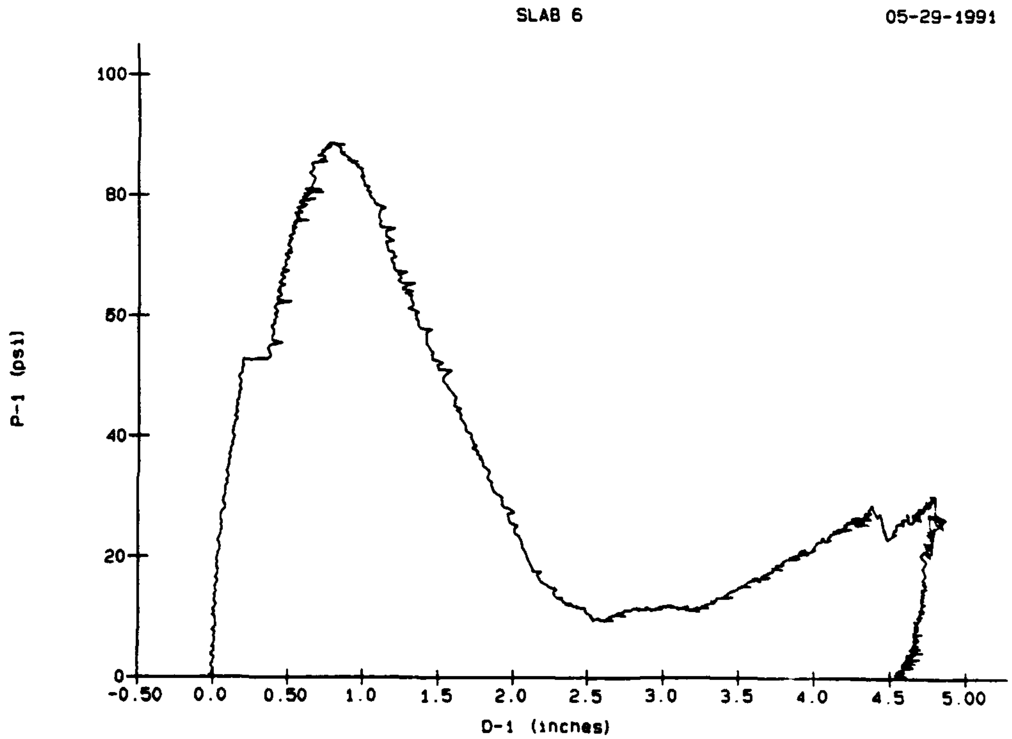


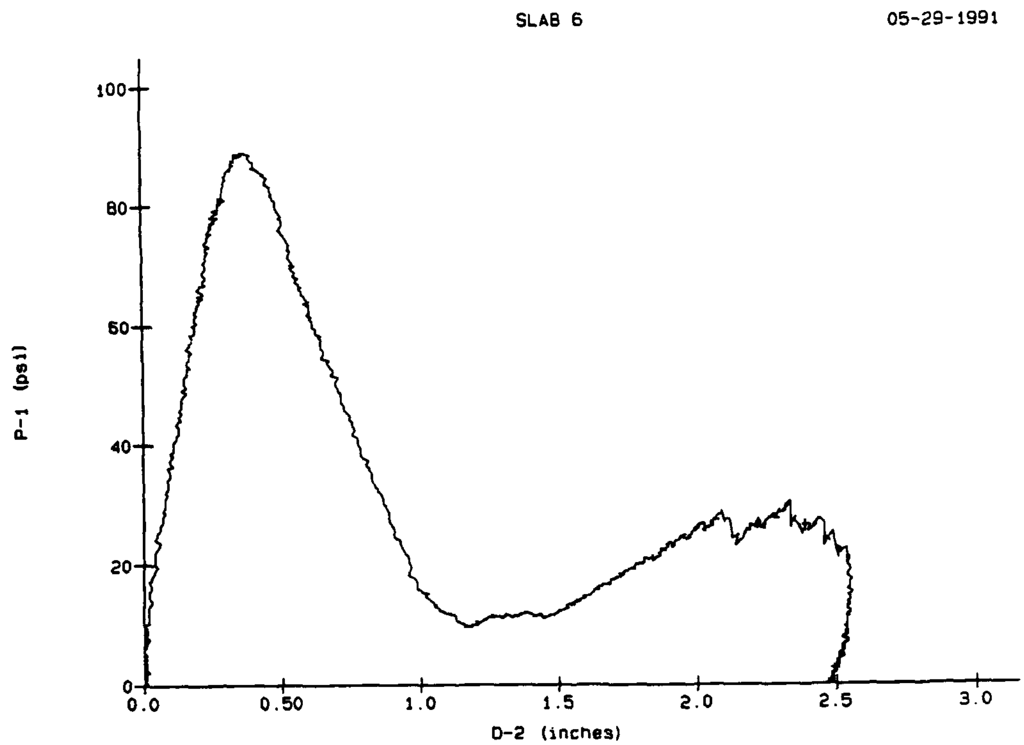
SLAB 5
05-16-1991
150
100
50
0
-50
-500
0
500
1000
1500
2000
2500
3000
SL-5 (micro inch/inch)
P-1 (psi)

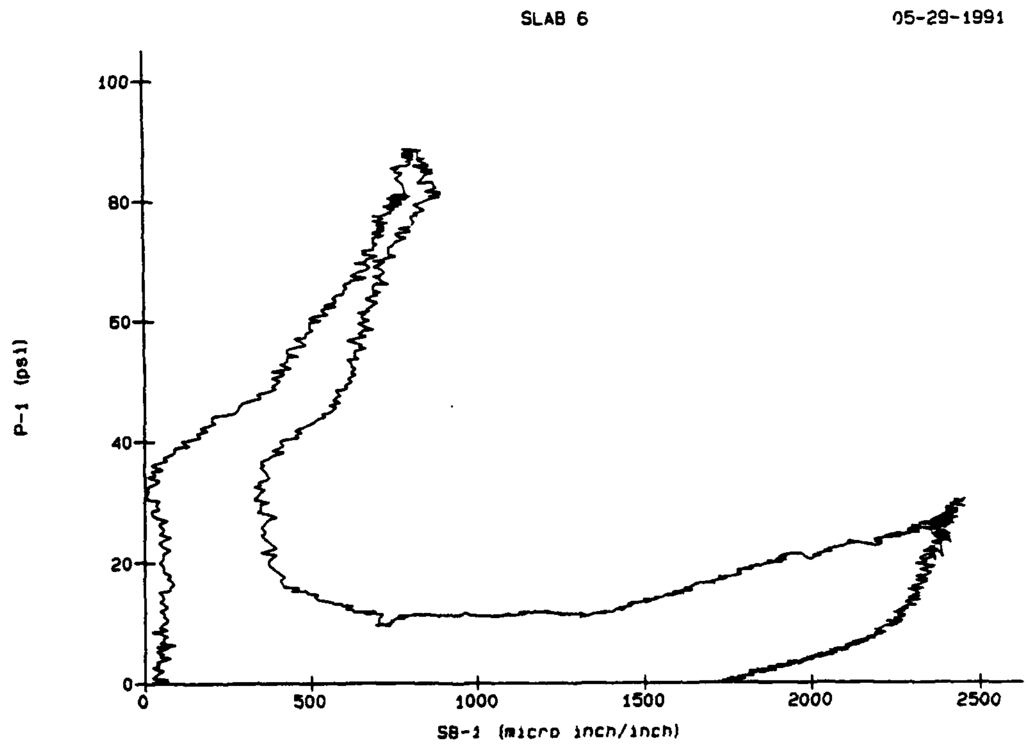

SLAB 5
05-16-1991
150
100
50
0
-50
P-1 (psi)
0
2000
4000
6000
8000
1.000E+4
1.200E+4
SL-6 (micro inch/inch)

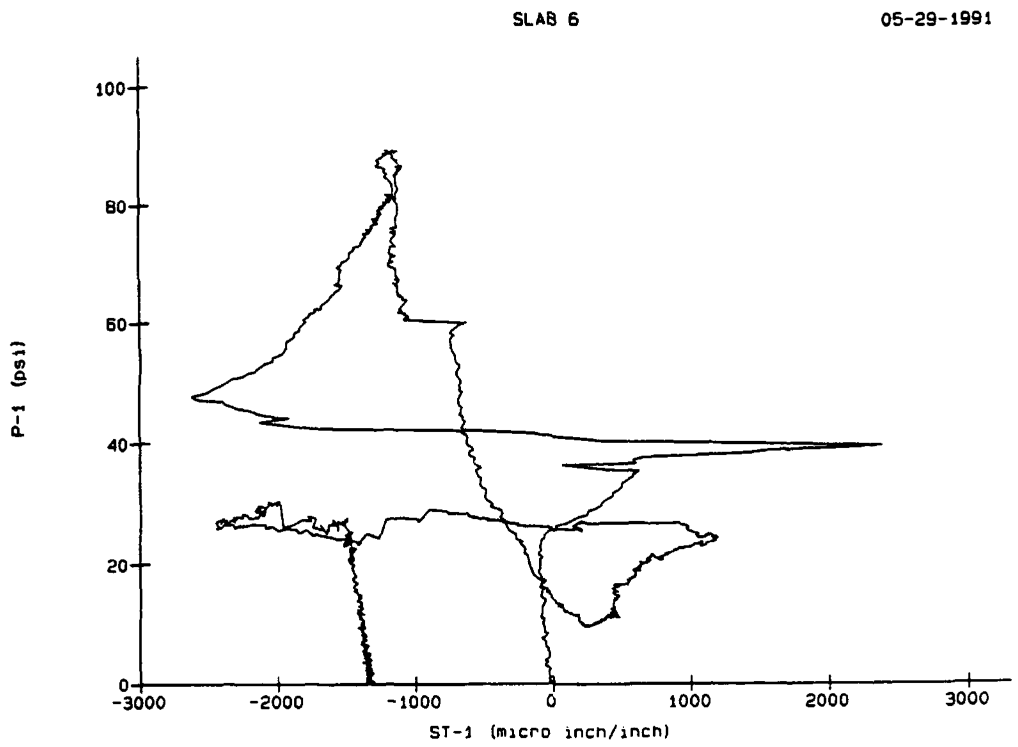

SLAB 5
05-16-1991
150
100
50
0
-50
P-2 (psi)
-2.000E+4
-1.500E+4
-1.000E+4
-5000
0
5000
ST-1 (micro inch/inch)


SLAB 6
P-1 (psi)
100
80
60
40
20
0
0
100
200
300
400
500
600
700
TIME (seconds)

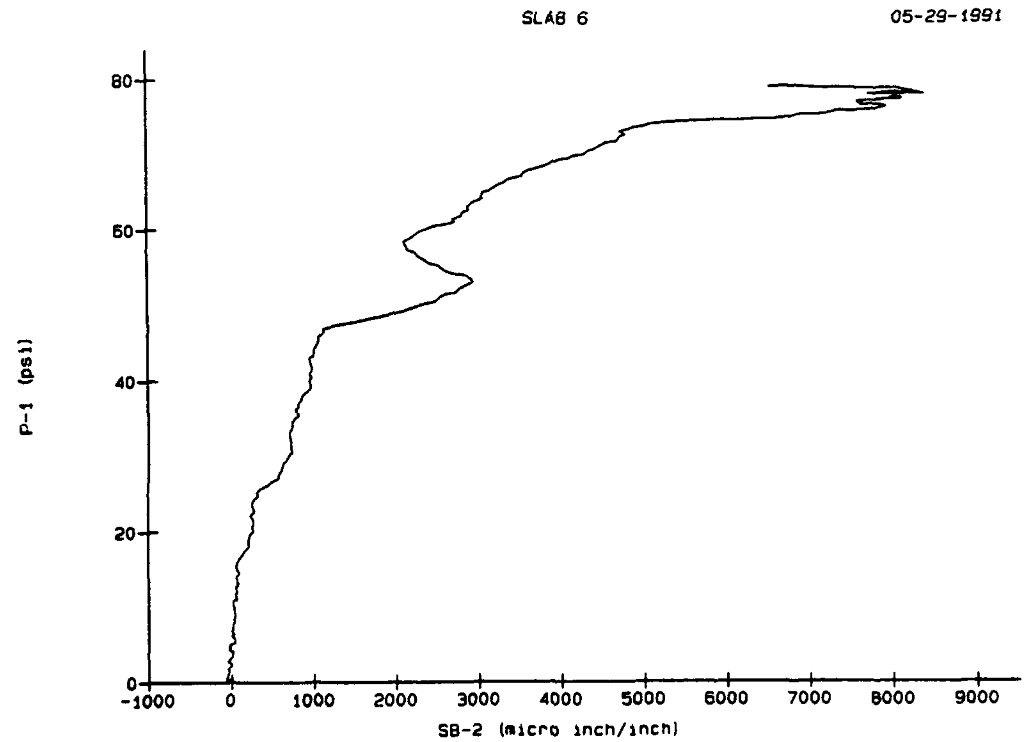

SLAB 6
05-29-1991
P-1 (psi)
100
80
60
40
20
0
-0.50
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.00
D-1 (inches)


SLAB 6
05-29-1991
100
80
60
40
20
0
P-1 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
3.0
D-2 (inches)

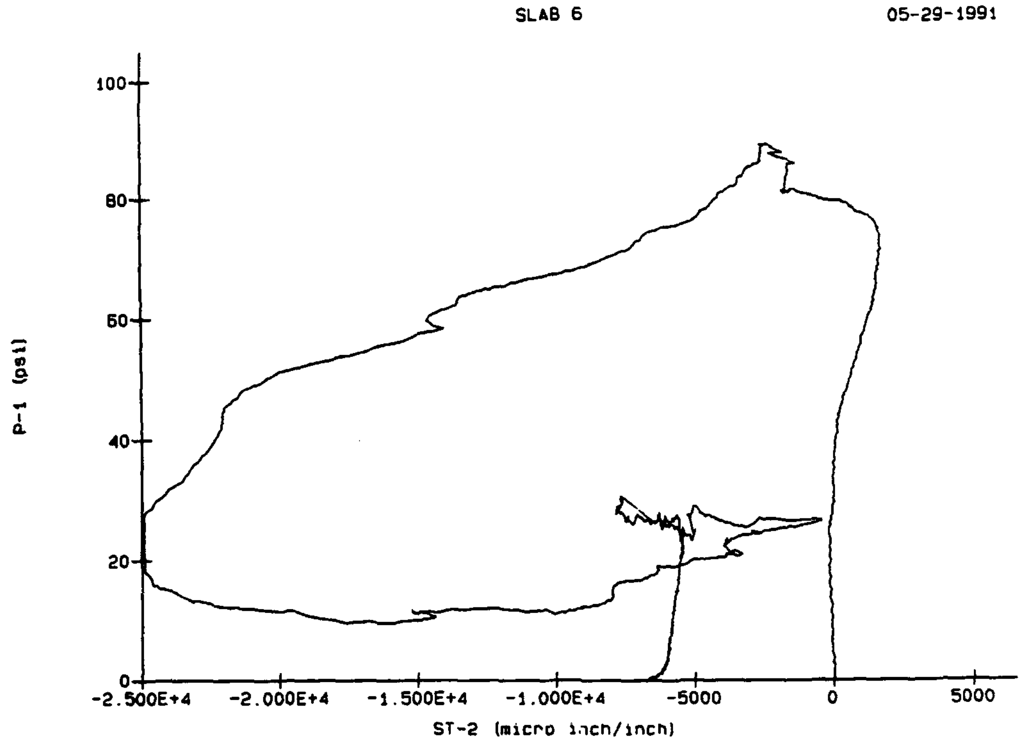

SLAB 6
05-29-1991
100
80
60
40
20
0
P-1 (psi)
0
500
1000
1500
2000
2500
SB-1 (micro inch/inch)



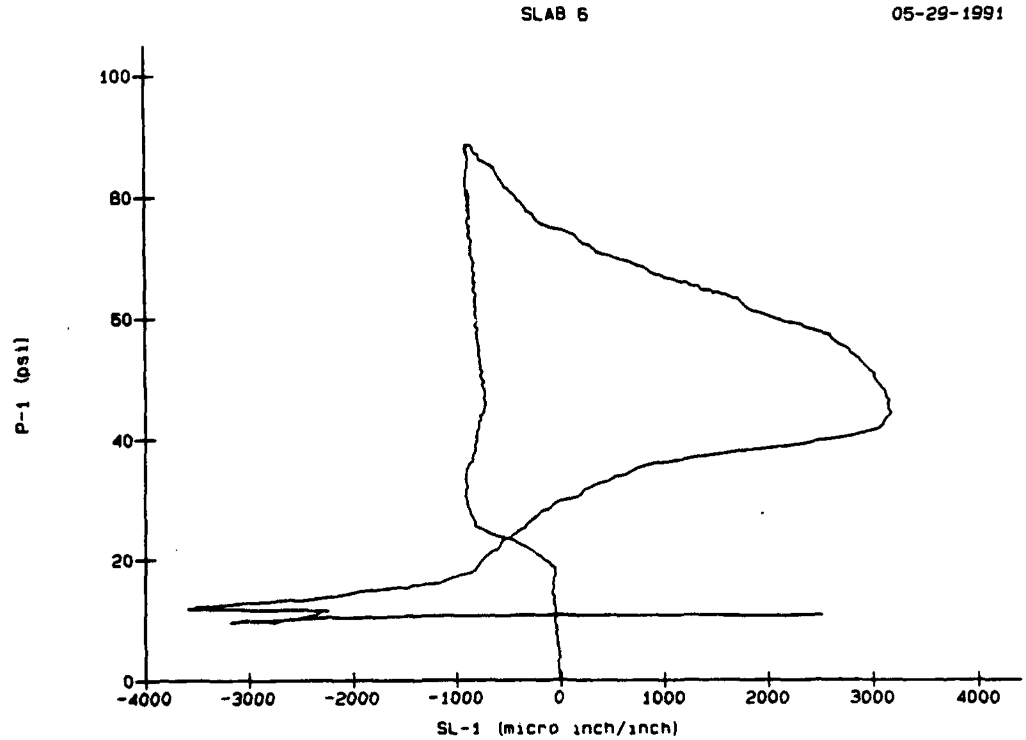
SLAB 6
05-29-1991
P-1 (psi)
100
80
60
40
20
0
-3000
-2000
-1000
0
1000
2000
3000
ST-1 (micro inch/inch)



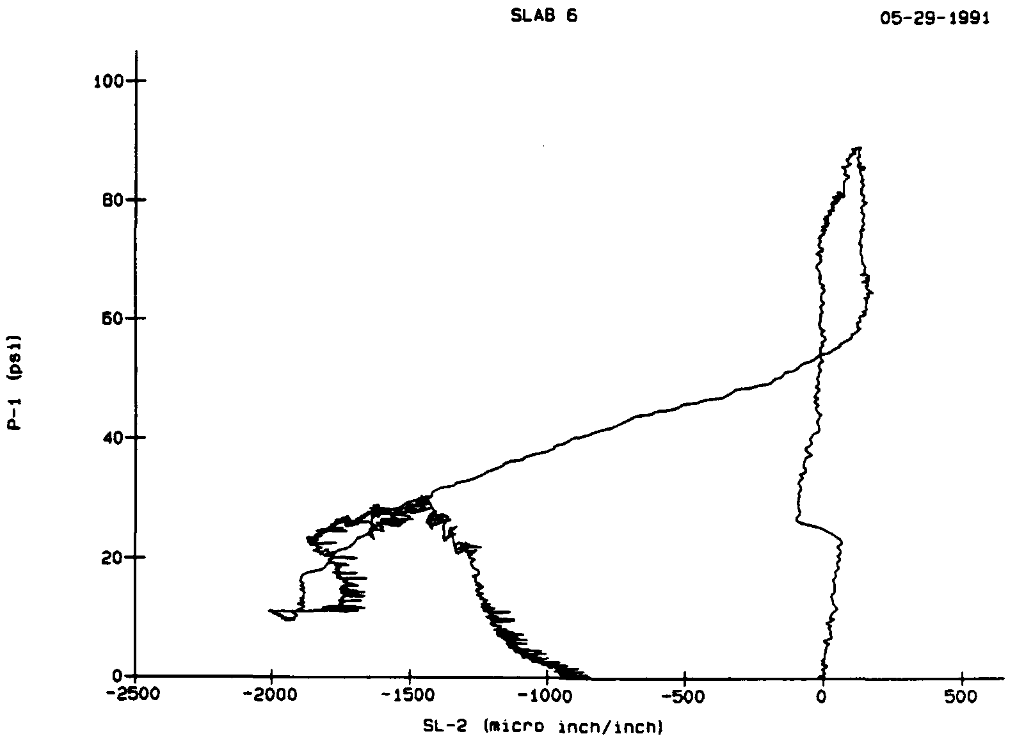
SLAB 6
05-29-1991
P-1 (psi)
80
60
40
20
0
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
SB-2 (micro inch/inch)

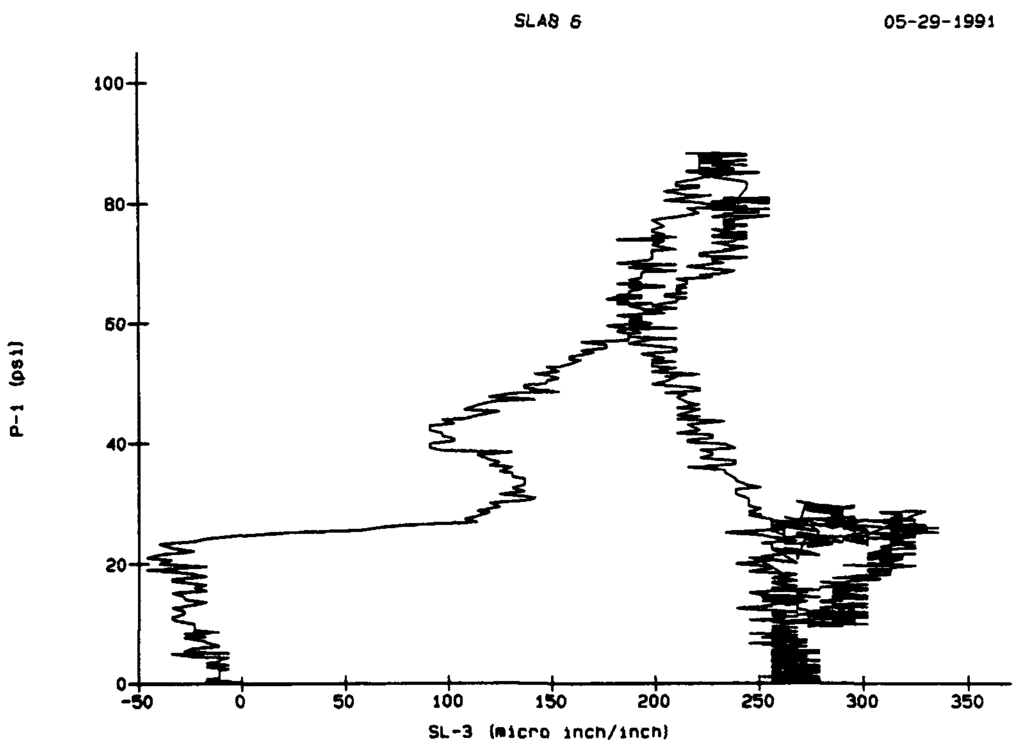


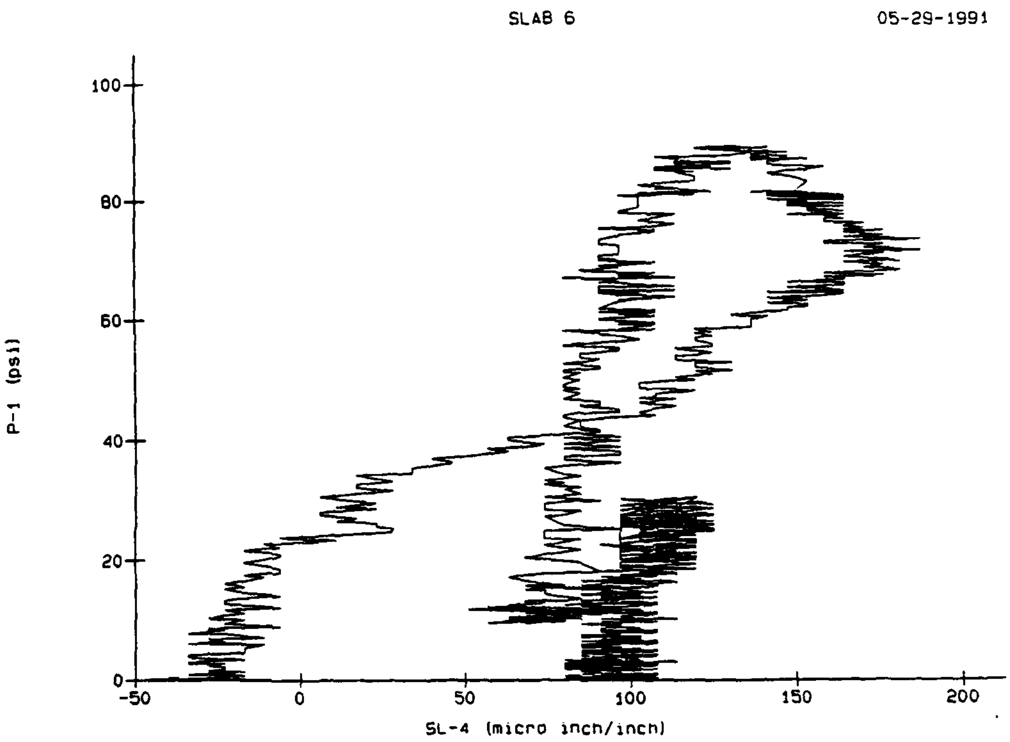
SLAB 6
05-29-1991
100
80
60
40
20
0
P-1 (psi)
-2.500E+4
-2.000E+4
-1.500E+4
-1.000E+4
-5000
0
5000
ST-2 (micro inch/inch)



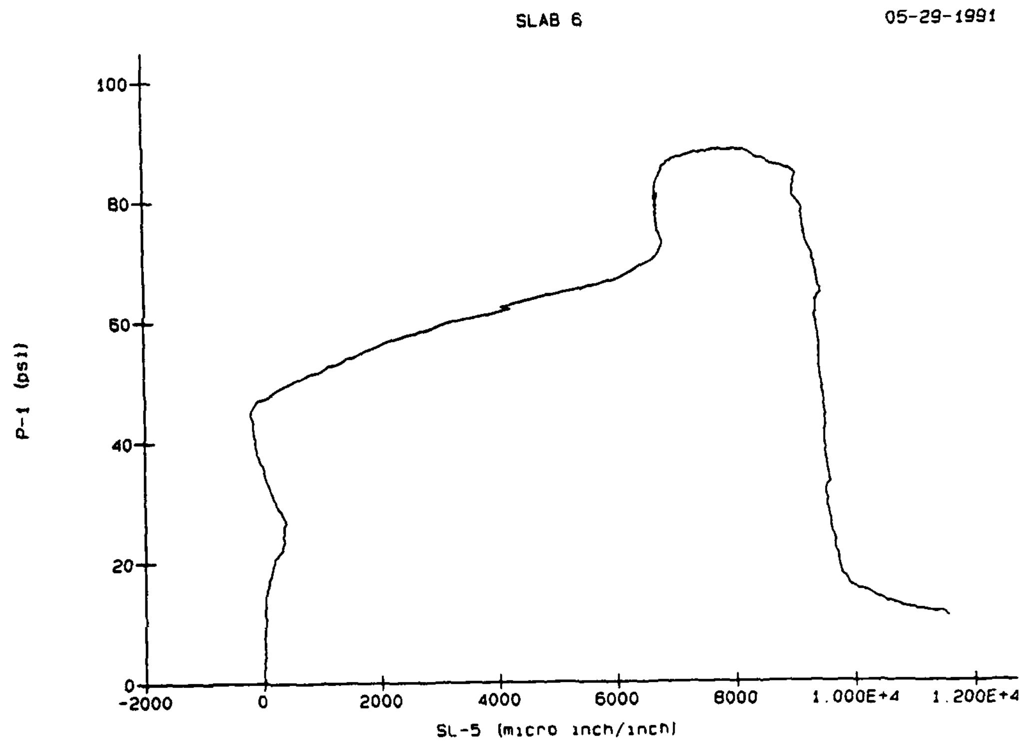
SLAB 6
05-29-1991
100
80
60
40
20
0
P-1 (psi)
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
SL-1 (micro inch/inch)


SLAB 6
05-29-1991
P-1 (psi)
SL-2 (micro inch/inch)
0
20
40
60
80
100
-2500
-2000
-1500
-1000
-500
0
500


SLAB 6
05-29-1991
P-1 (psi)
SL-3 (micro inch/inch)
0
20
40
60
80
100
-50
0
50
100
150
200
250
300
350

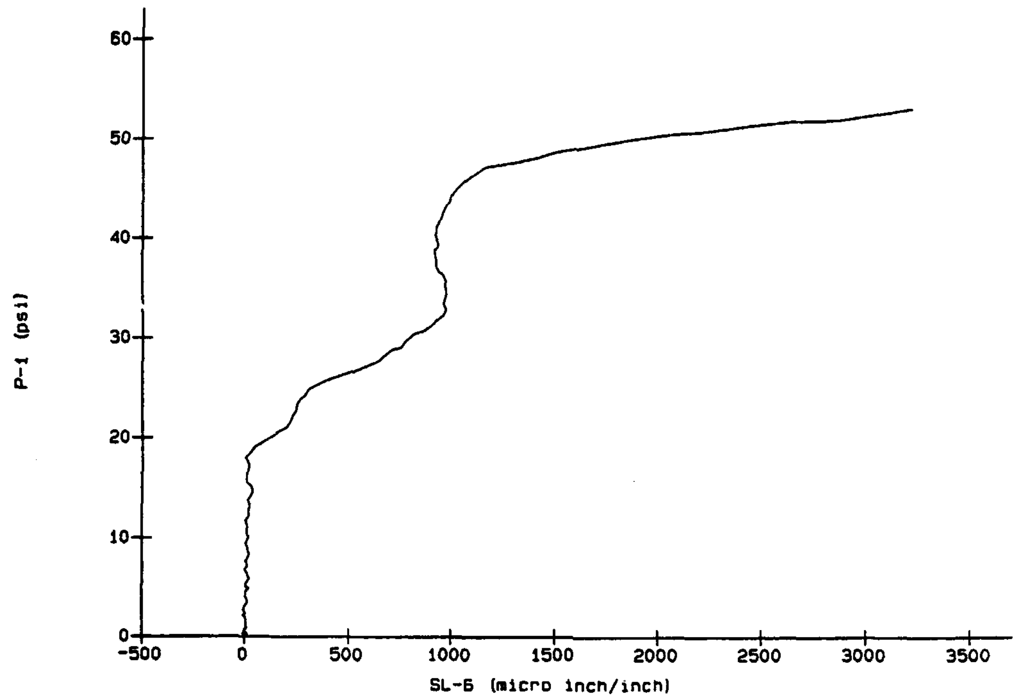


SLAB 6
05-29-1991
P-1 (psi)
100
80
60
40
20
0
-50
0
50
100
150
200
SL-4 (micro inch/inch)

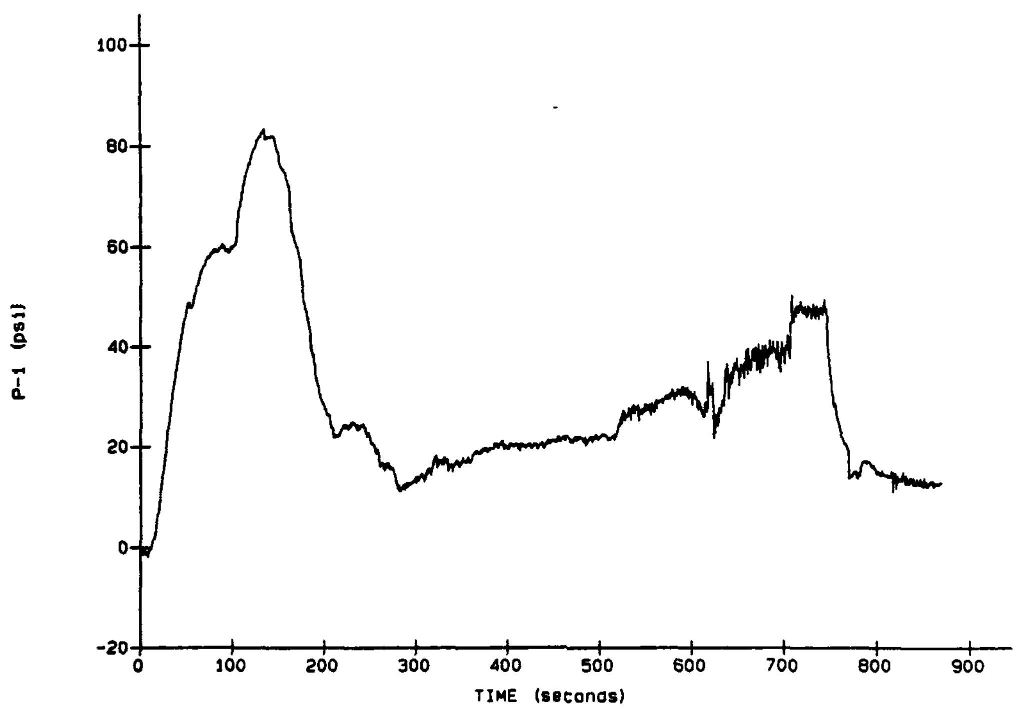


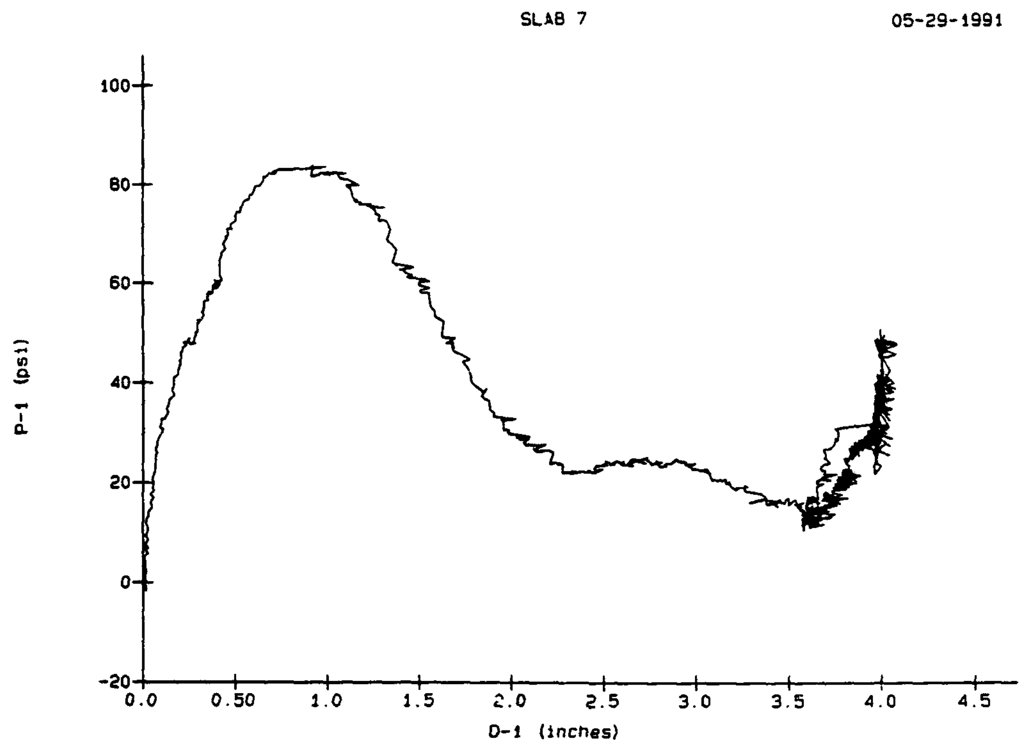
SLAB 6
05-29-1991
P-1 (psi)
100
80
60
40
20
0
-2000
0
2000
4000
6000
8000
1.000E+4
1.200E+4
SL-5 (micro inch/inch)

SLAB 6

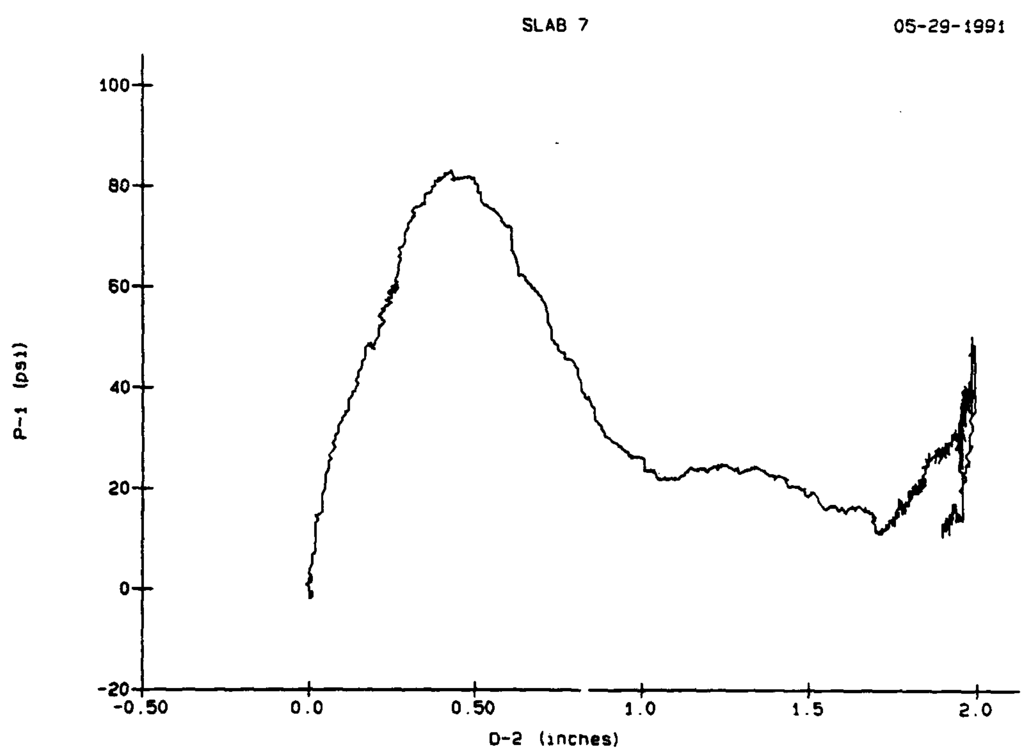

60
50
40
30
20
10
0
P-1 (psi)
-500
0
500
1000
1500
2000
2500
3000
3500
SL-6 (micro inch/inch)

SLAB 7

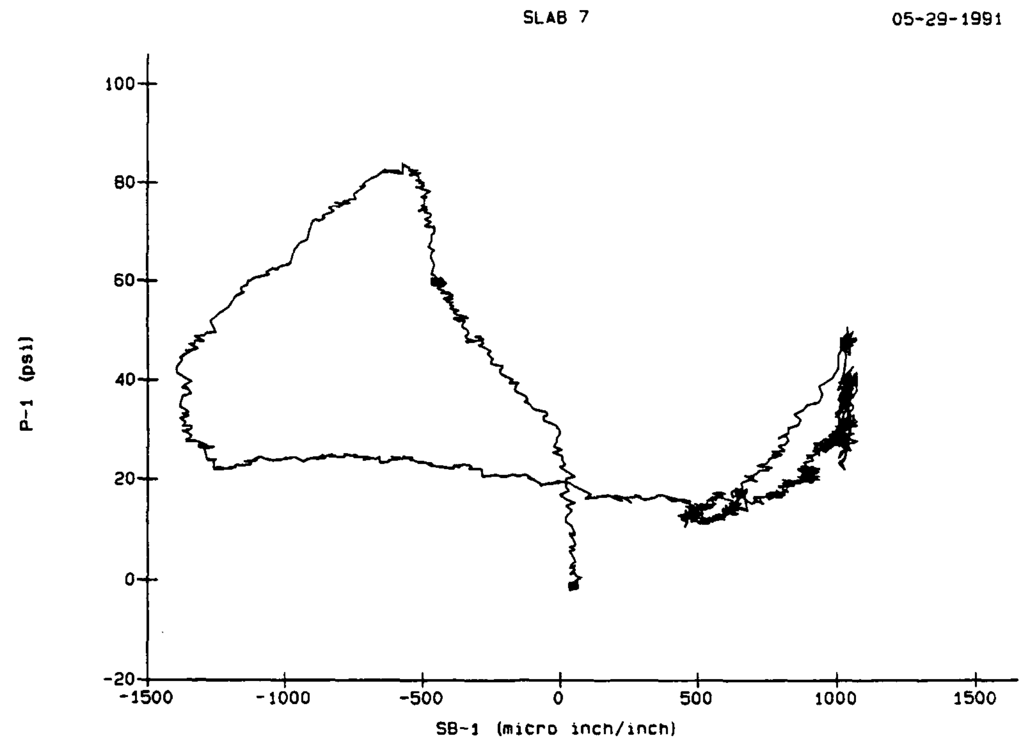

100
80
60
40
20
0
-20
P-1 (psi)
0
100
200
300
400
500
600
700
800
900
TIME (seconds)

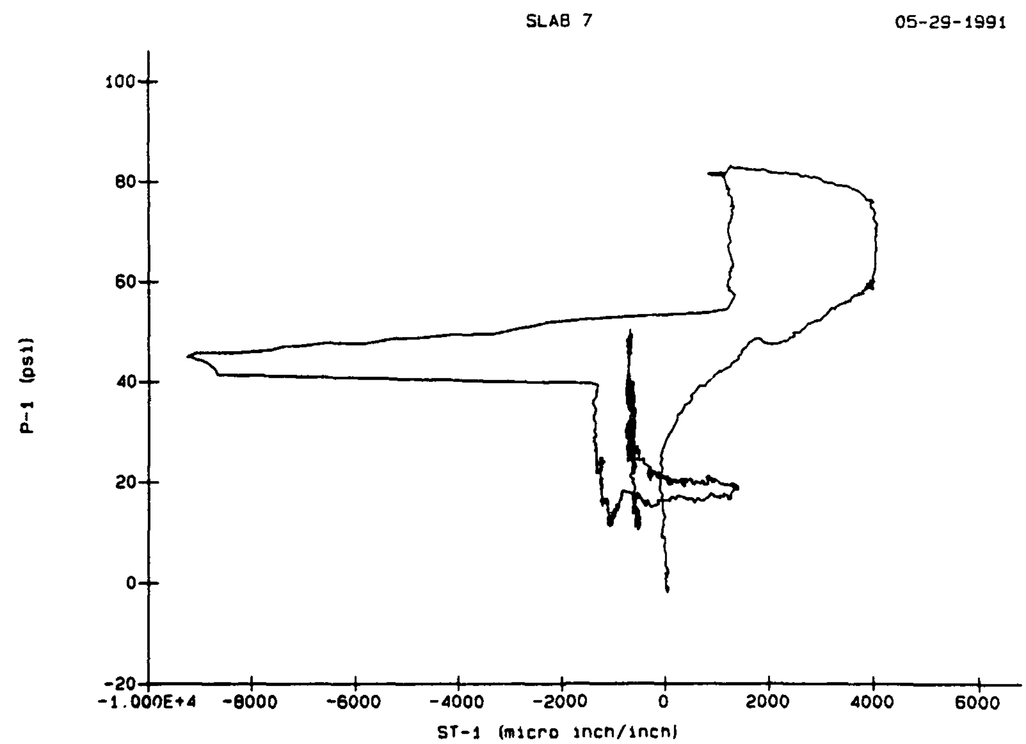


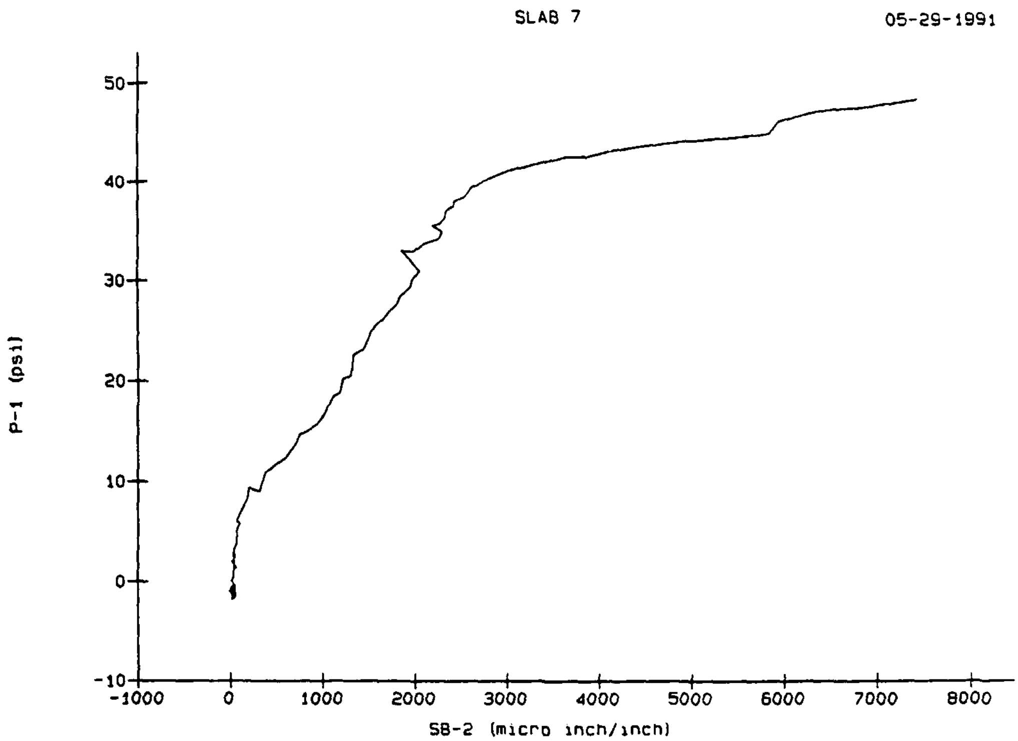
SLAB 7
05-29-1991
P-1 (psi)
D-1 (inches)
100
80
60
40
20
0
-20
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5

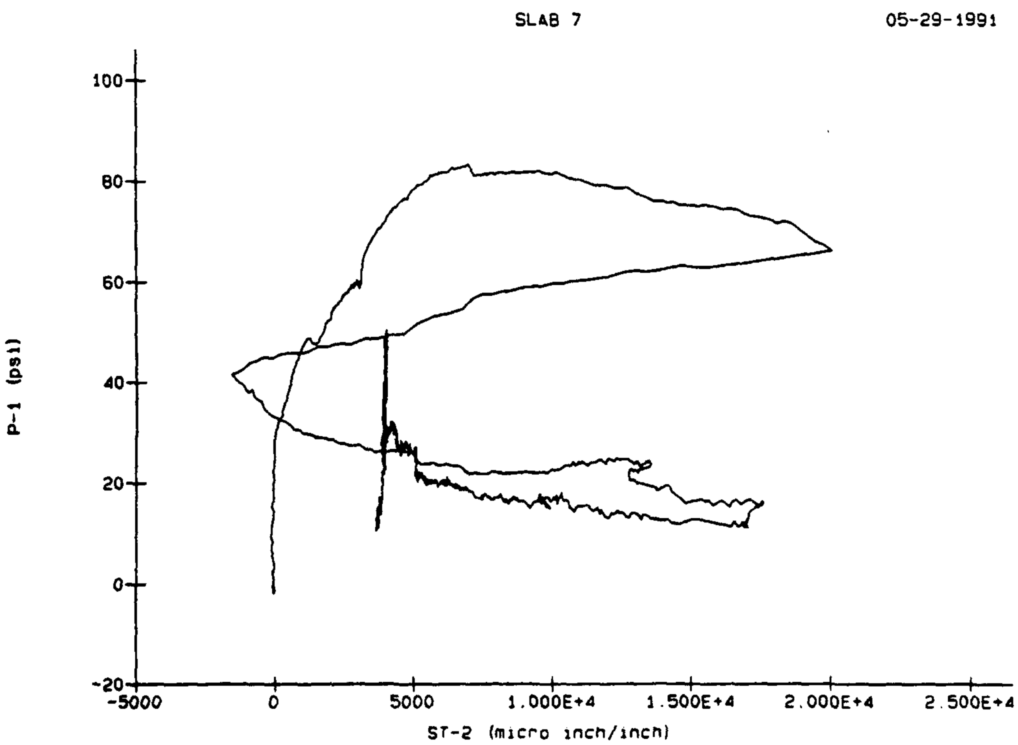


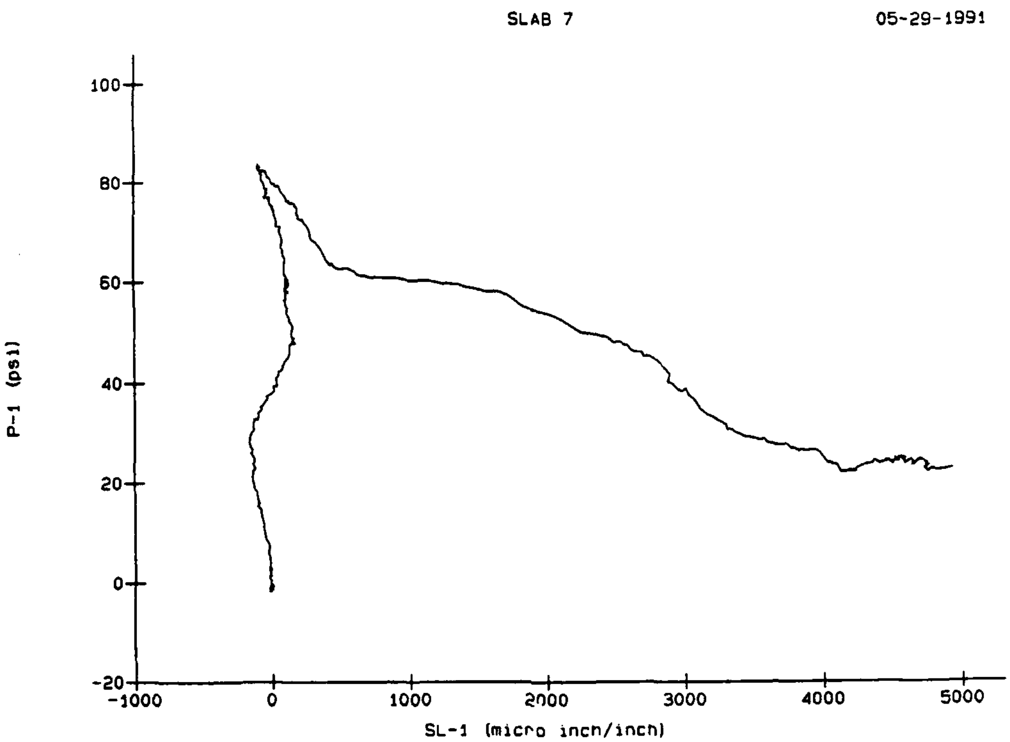
SLAB 7
05-29-1991
P-1 (psi)
D-2 (inches)
100
80
60
40
20
0
-20
-0.50
0.0
0.50
1.0
1.5
2.0

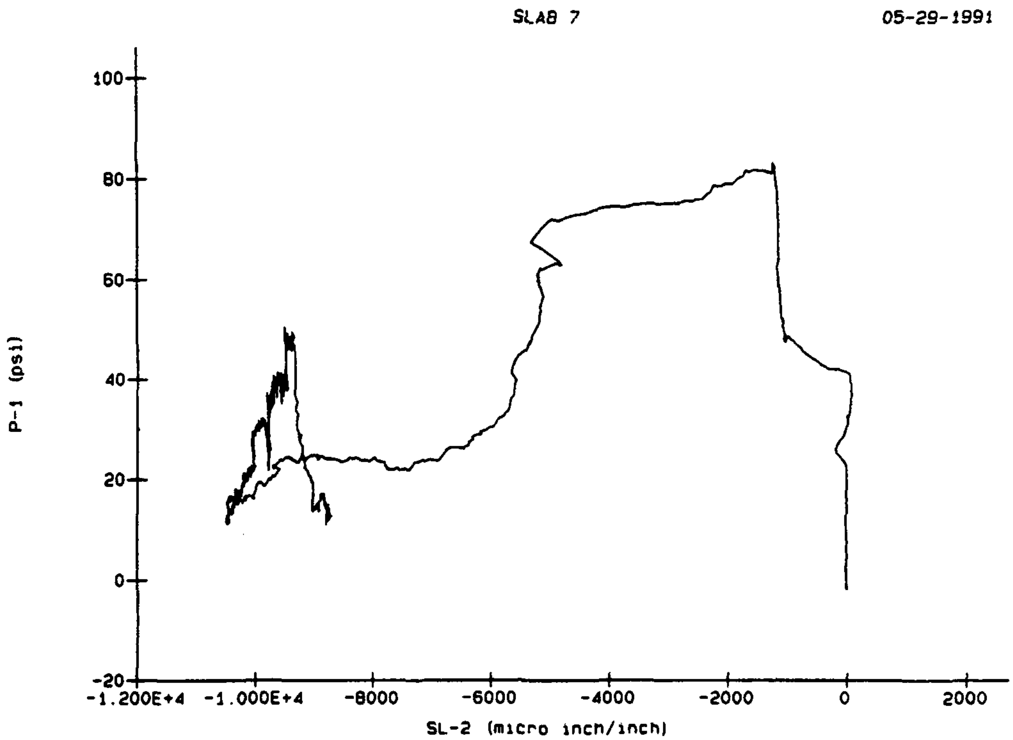

SLAB 7
05-29-1991
100
80
60
40
20
0
-20
P-1 (psi)
-1500
-1000
-500
0
500
1000
1500
SB-1 (micro inch/inch)

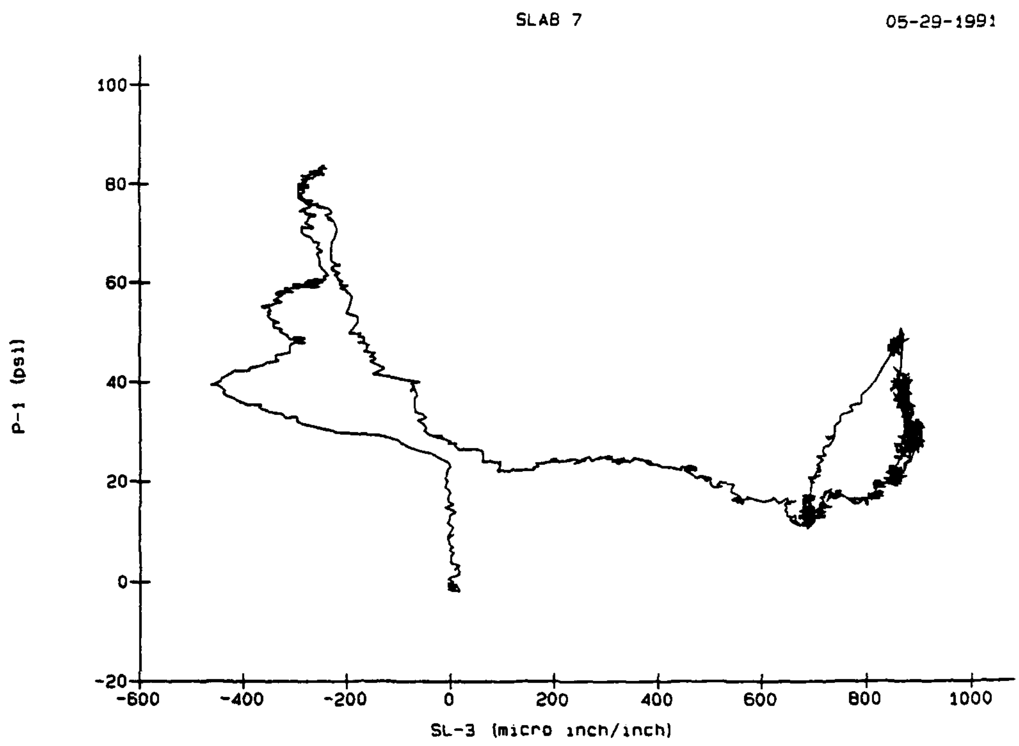

SLAB 7
05-29-1991
100
80
60
40
20
0
-20
P-1 (psi)
-1.000E+4
-8000
-6000
-4000
-2000
0
2000
4000
6000
ST-1 (micro inch/inch)

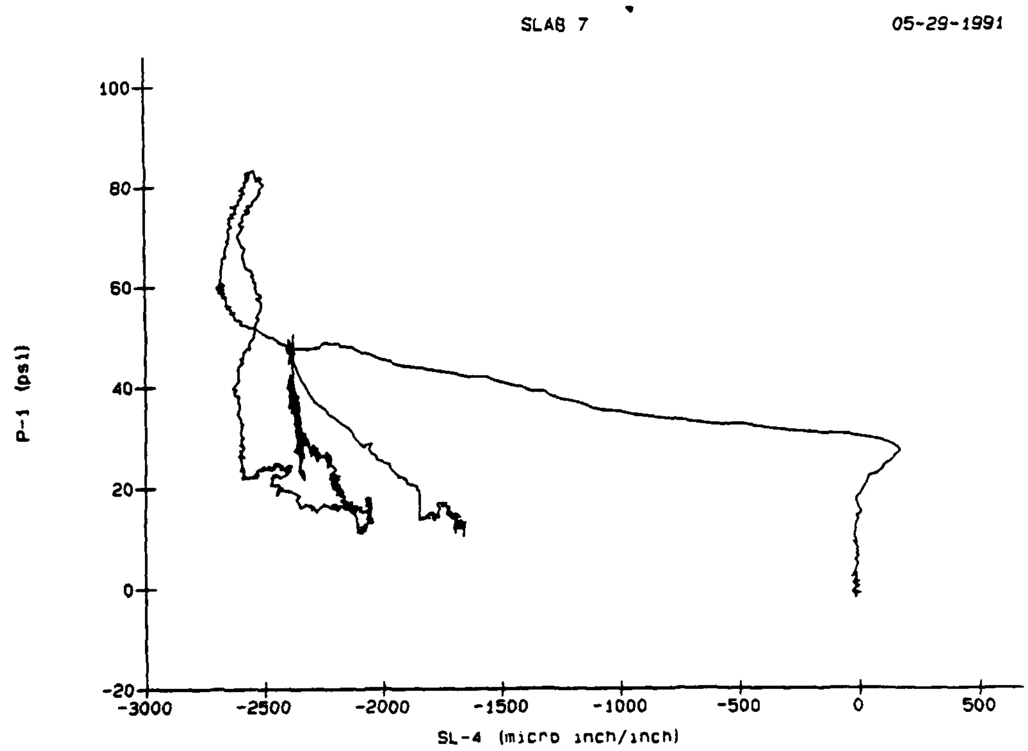

SLAB 7
05-29-1991
P-1 (psi)
50
40
30
20
10
0
-10
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
SB-2 (micro inch/inch)

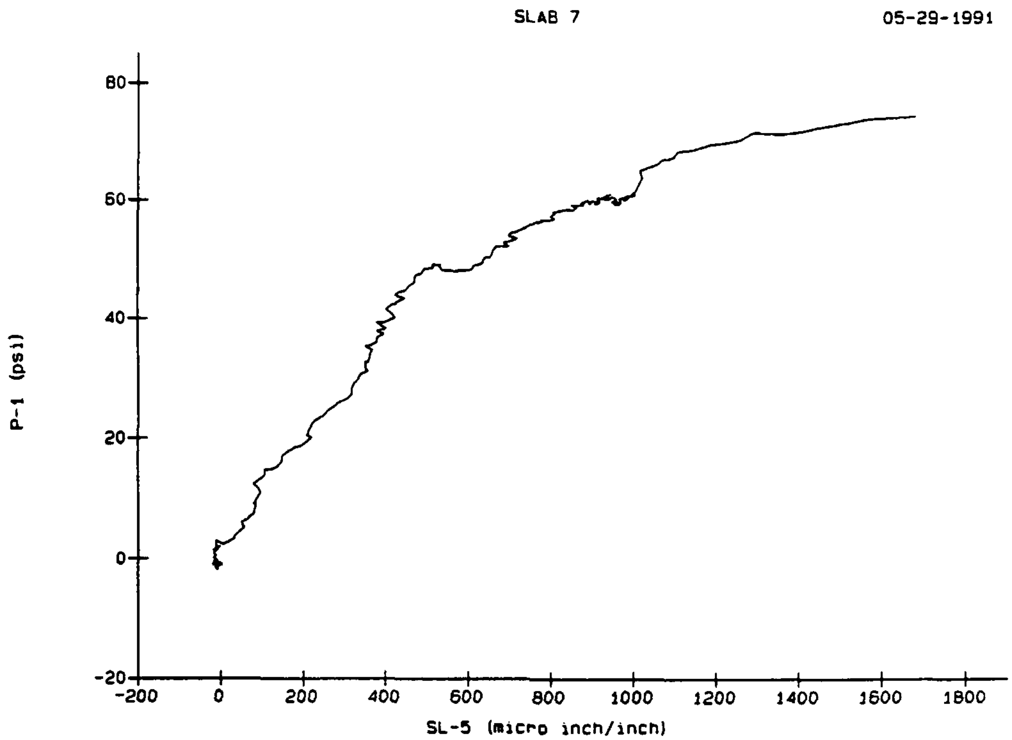

SLAB 7
05-29-1991
P-1 (psi)
100
80
60
40
20
0
-20
-5000
0
5000
1.000E+4
1.500E+4
2.000E+4
2.500E+4
ST-2 (micro inch/inch)

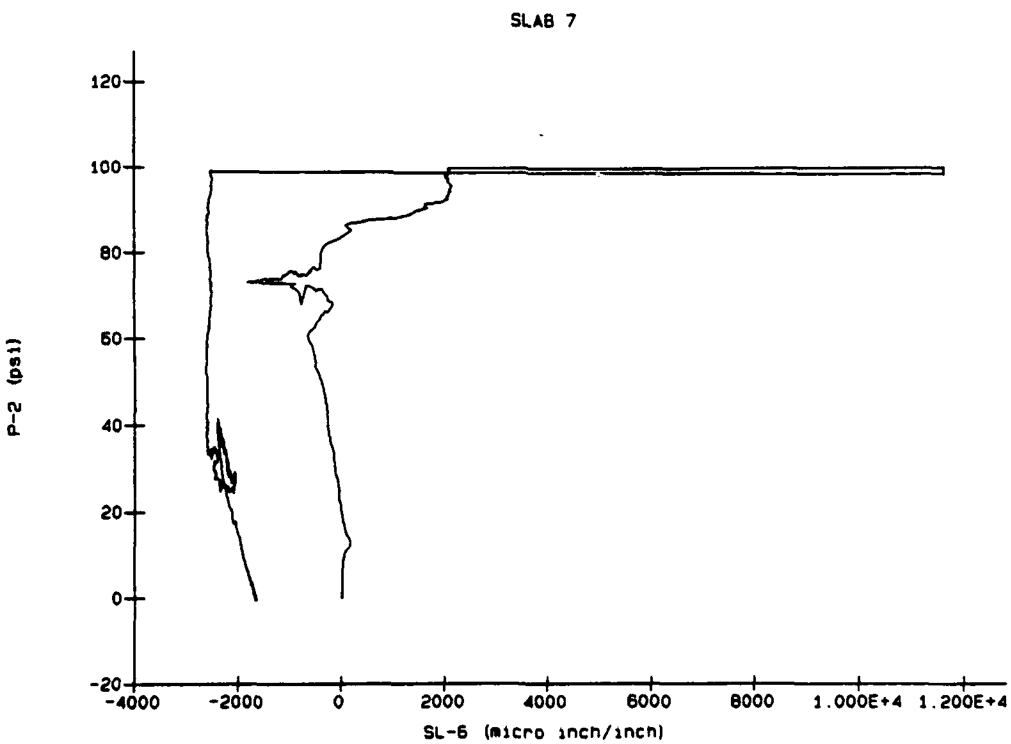

SLAB 7
05-29-1991
P-1 (psi)
100
80
60
40
20
0
-20
-1000
0
1000
2000
3000
4000
5000
SL-1 (micro inch/inch)


SLAB 7
05-29-1991
P-1 (psi)
100
80
60
40
20
0
-20
-1.200E+4
-1.000E+4
-8000
-6000
-4000
-2000
0
2000
SL-2 (micro inch/inch)

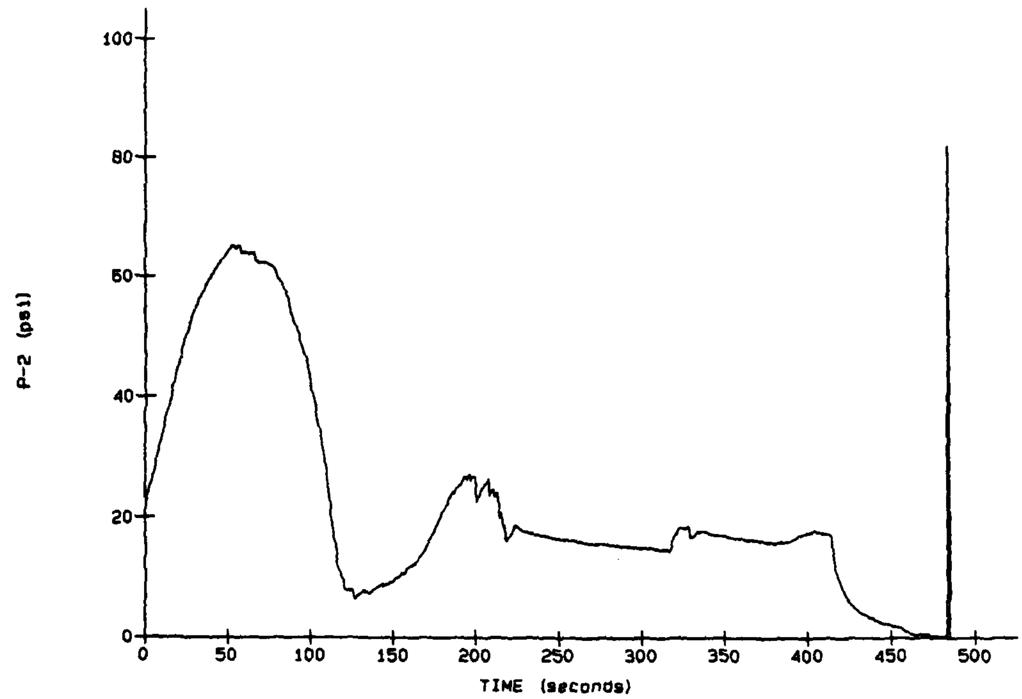

SLAB 7
05-29-1991
P-1 (psi)
SL-3 (micro inch/inch)
100
80
60
40
20
0
-20
-600
-400
-200
0
200
400
600
800
1000


SLAB 7
05-29-1991
P-1 (psi)
SL-4 (micro inch/inch)
100
80
60
40
20
0
-20
-3000
-2500
-2000
-1500
-1000
-500
0
500


SLAB 7
05-29-1991
P-1 (psi)
80
60
40
20
0
-20
-200
0
200
400
600
800
1000
1200
1400
1600
1800
SL-5 (micro inch/inch)

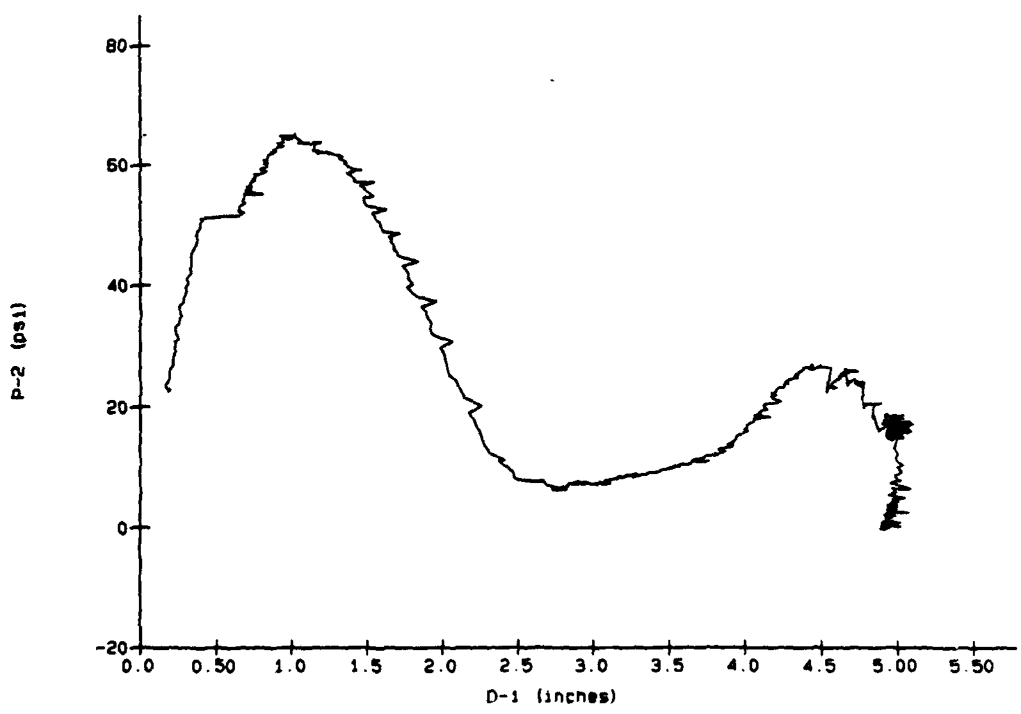

SLAB 7
P-2 (psi)
120
100
80
60
40
20
0
-20
-4000
-2000
0
2000
4000
6000
8000
1.000E+4
1.200E+4
SL-6 (micro inch/inch)

SLAB 8



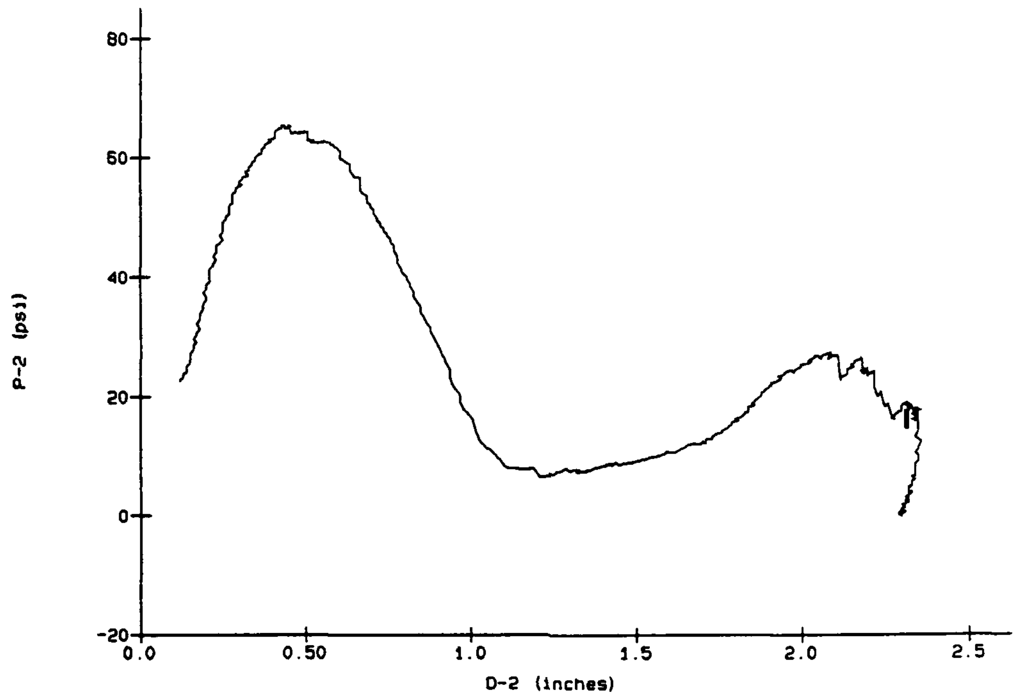
P-2 (psi)
100
80
60
40
20
0
0
50
100
150
200
250
300
350
400
450
500
TIME (seconds)

SLAB 8

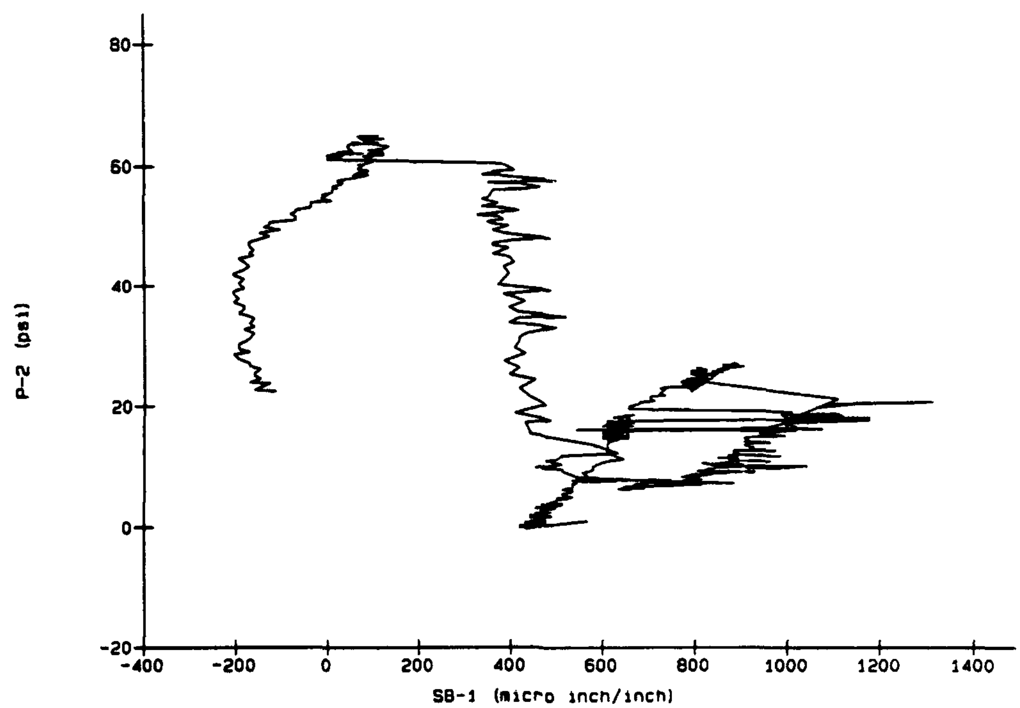


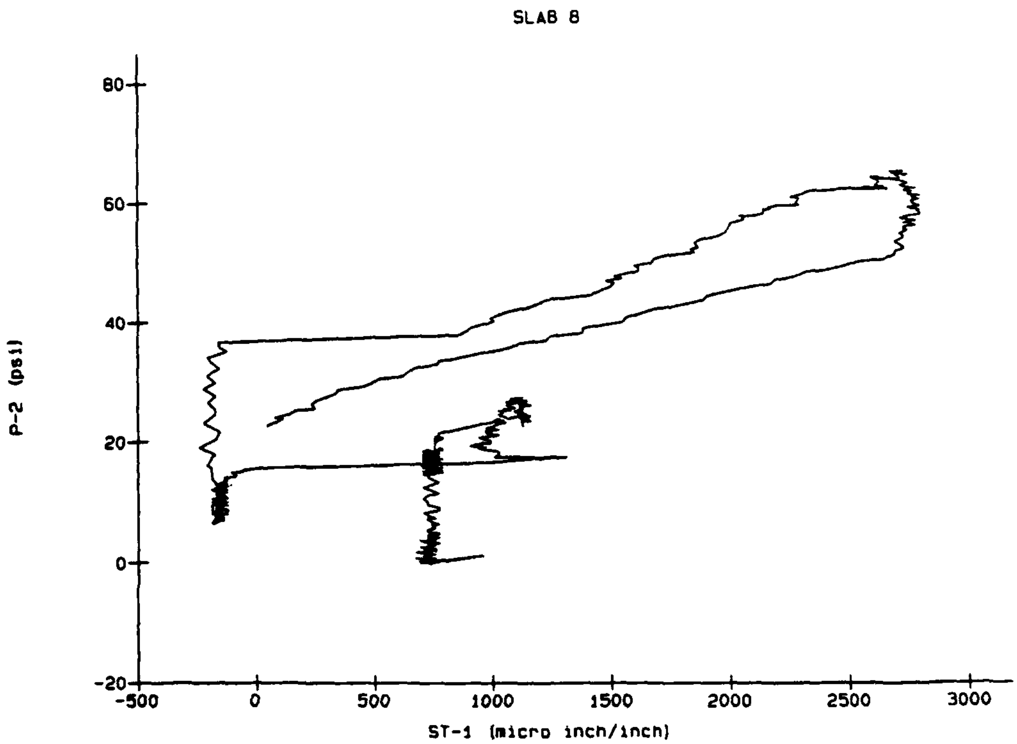
P-2 (psi)
80
60
40
20
0
-20
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.00
5.50
D-1 (inches)

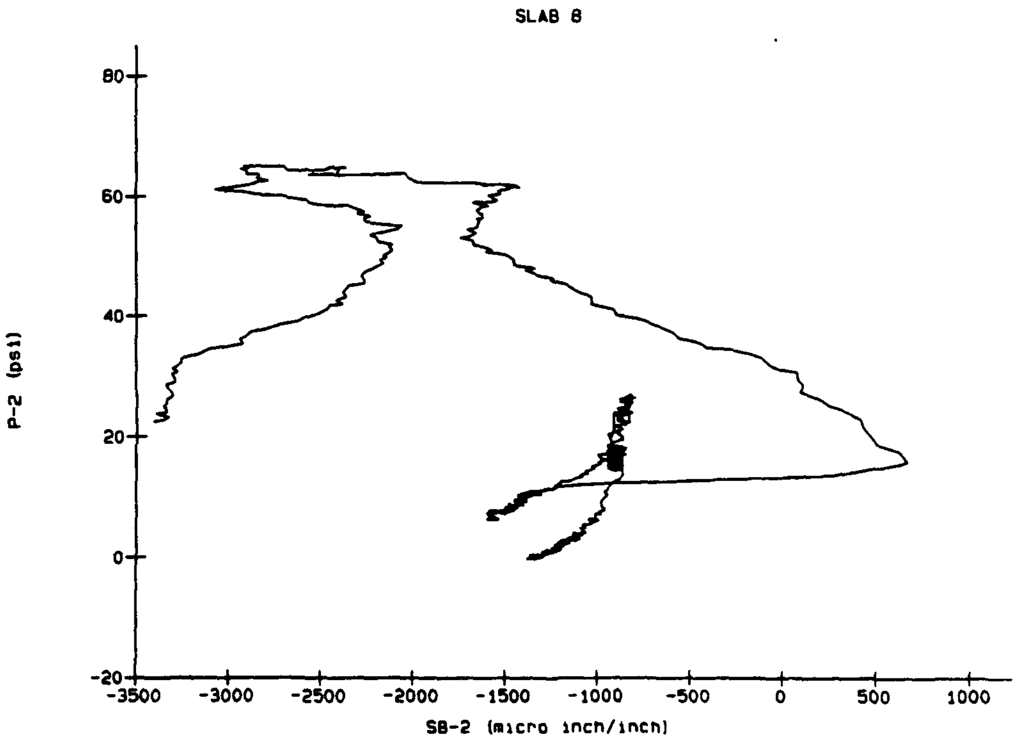
SLAB 8

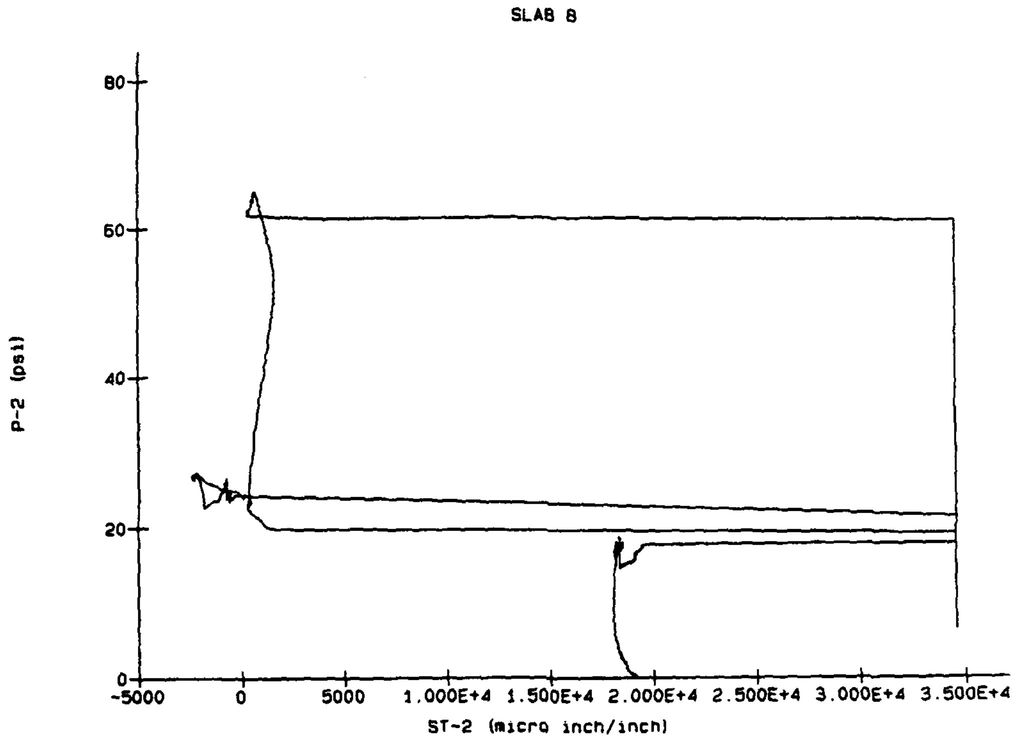

80
60
40
20
0
-20
P-2 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
D-2 (inches)

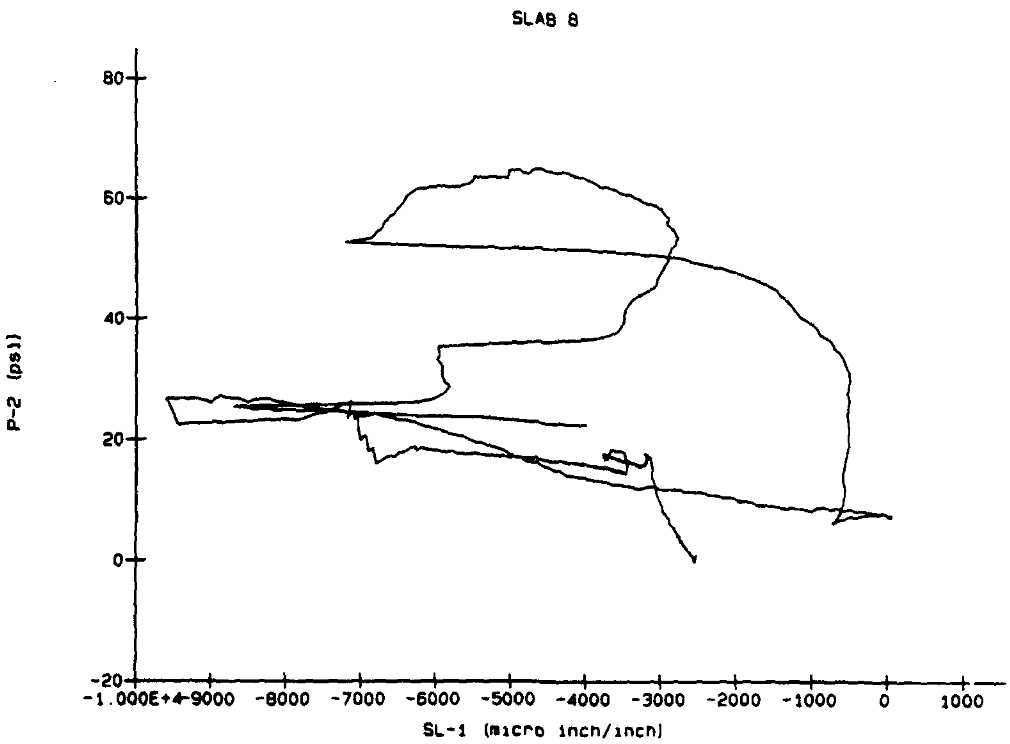
SLAB 8


80
60
40
20
0
-20
P-2 (psi)
-400
-200
0
200
400
600
800
1000
1200
1400
SB-1 (micro inch/inch)

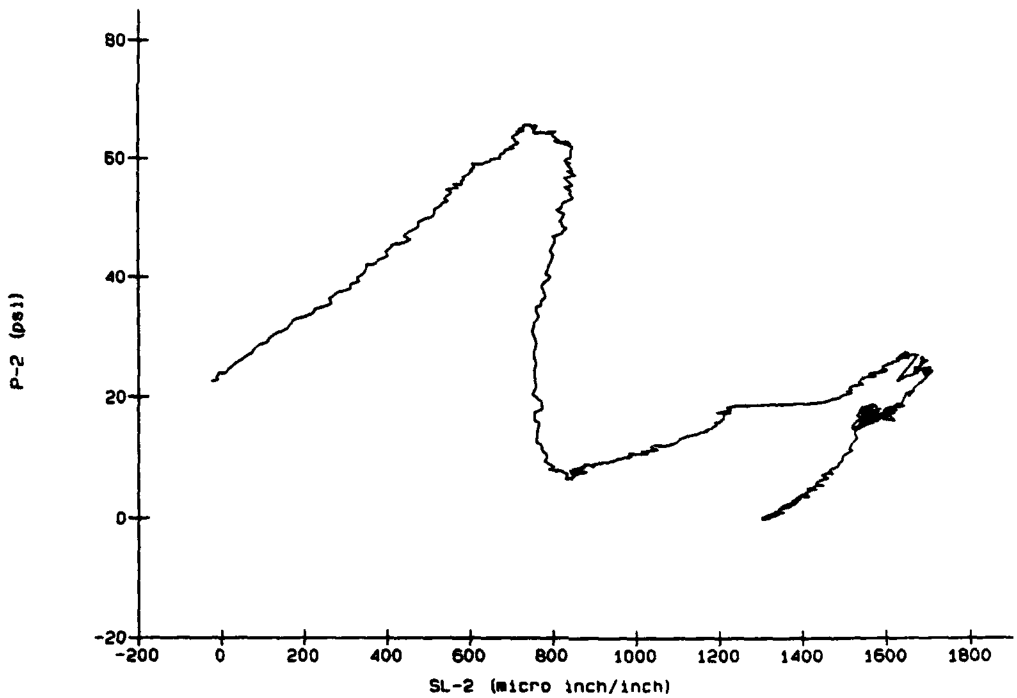

SLAB 8
P-2 (psi)
80
60
40
20
0
-20
-500
0
500
1000
1500
2000
2500
3000
ST-1 (micro inch/inch)


SLAB 8
P-2 (psi)
80
60
40
20
0
-20
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
SB-2 (micro inch/inch)

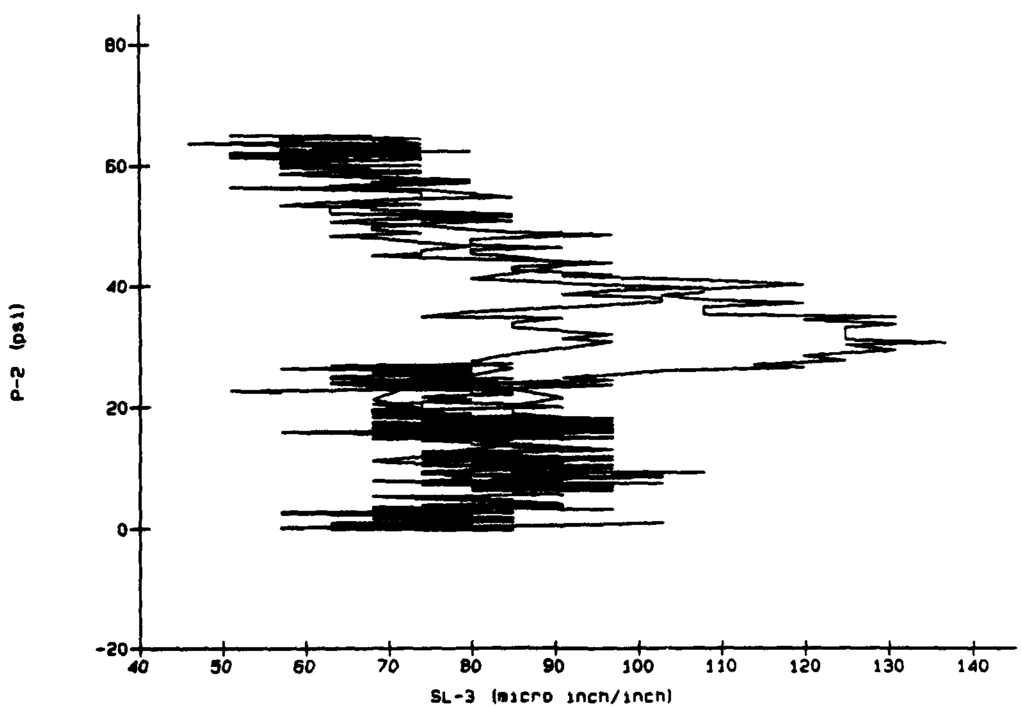

SLAB 8
P-2 (psi)
80
60
40
20
0
-5000
0
5000
1.000E+4
1.500E+4
2.000E+4
2.500E+4
3.000E+4
3.500E+4
ST-2 (micro inch/inch)

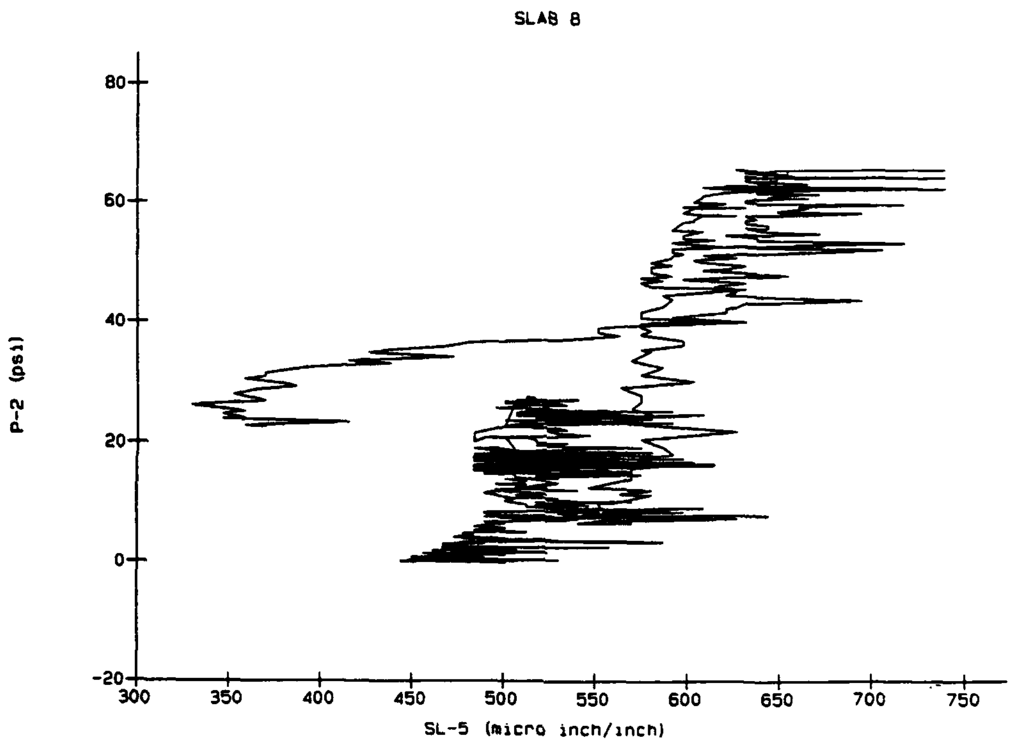

SLAB 8
P-2 (psi)
80
60
40
20
0
-20
-1.000E+4
-9000
-8000
-7000
-6000
-5000
-4000
-3000
-2000
-1000
0
1000
SL-1 (micro inch/inch)

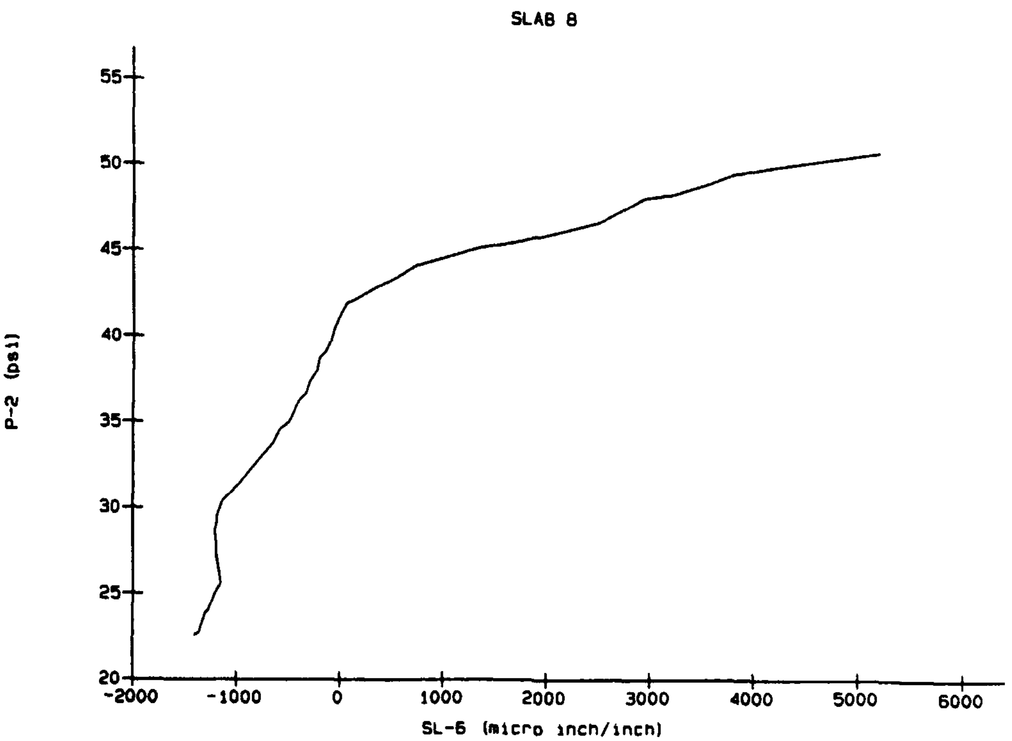
SLAB 8

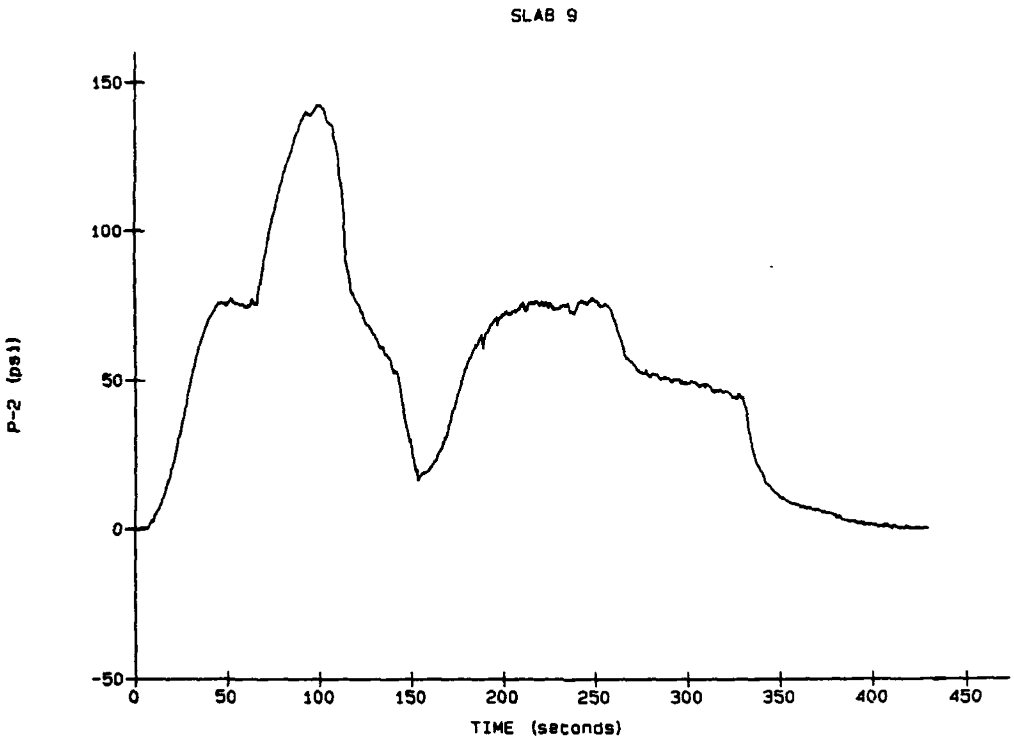

80
60
40
20
0
-20
P-2 (psi)
-200
0
200
400
600
800
1000
1200
1400
1600
1800
SL-2 (micro inch/inch)

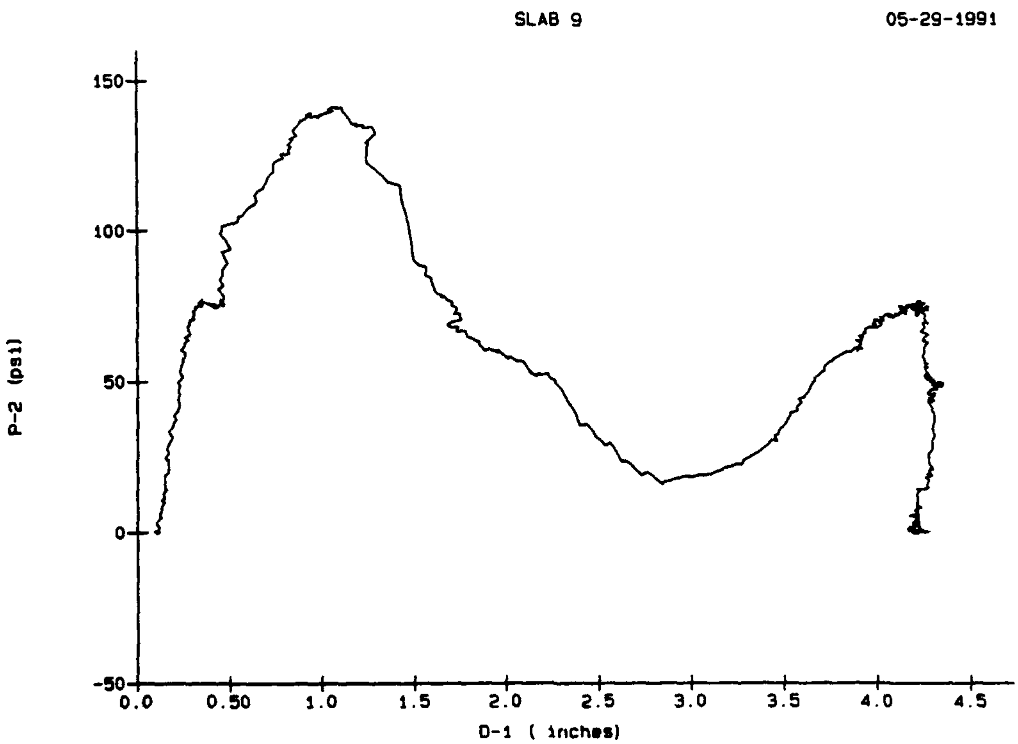
SLAB 8

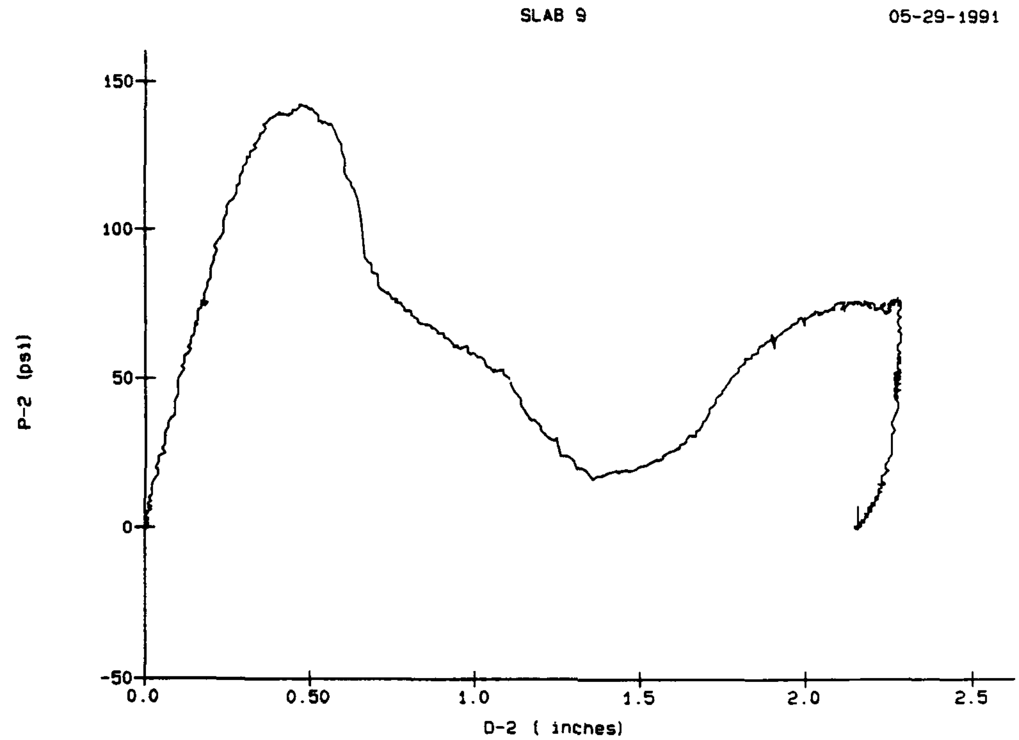

80
60
40
20
0
-20
P-2 (psi)
40
50
60
70
80
90
100
110
120
130
140
SL-3 (micro inch/inch)

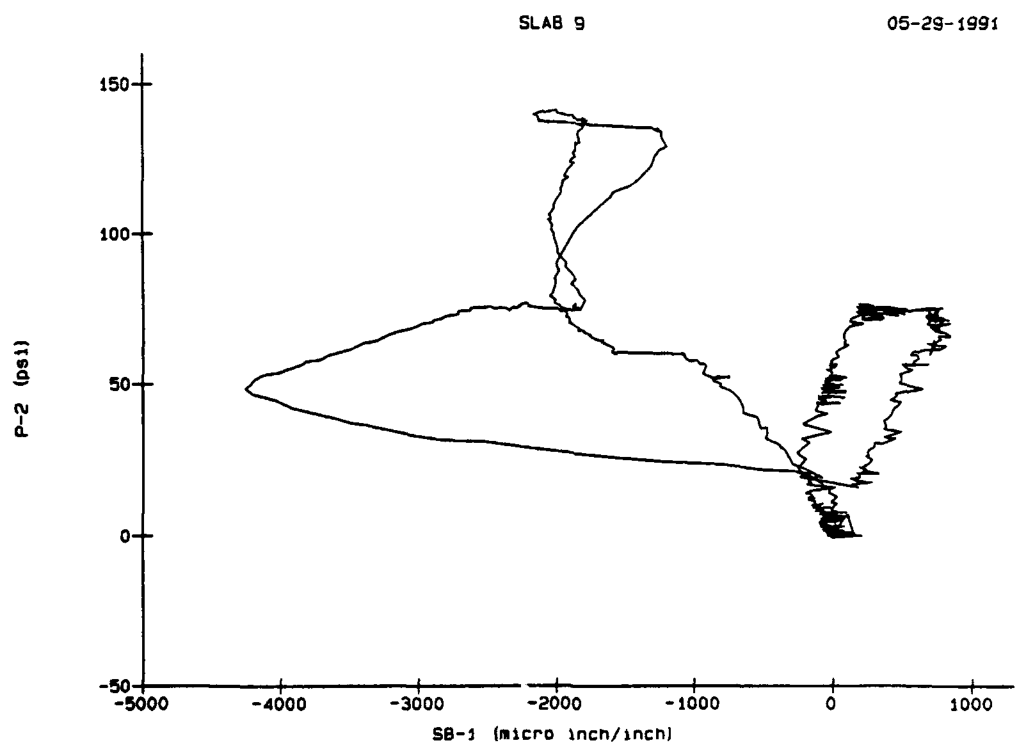

SLAB 8
P-2 (psi)
SL-5 (micro inch/inch)
80
60
40
20
0
-20
300
350
400
450
500
550
600
650
700
750

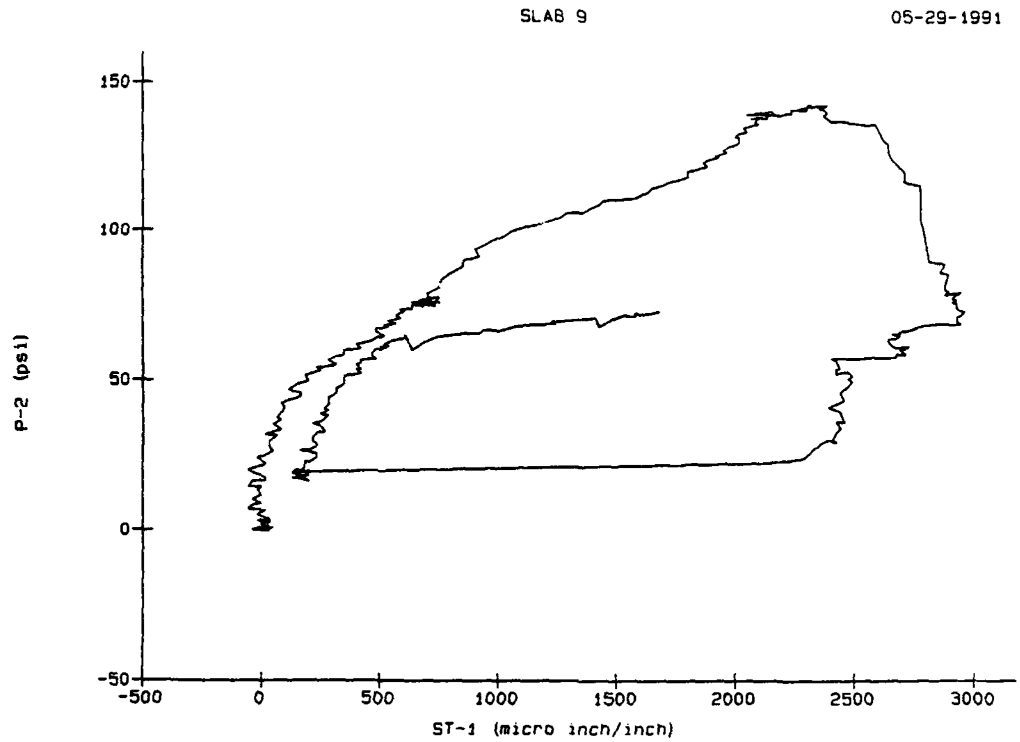

SLAB 8
P-2 (psi)
SL-6 (micro inch/inch)
55
50
45
40
35
30
25
20
-2000
-1000
0
1000
2000
3000
4000
5000
6000


SLAB 9
150
100
50
0
-50
P-2 (psi)
0
50
100
150
200
250
300
350
400
450
TIME (seconds)

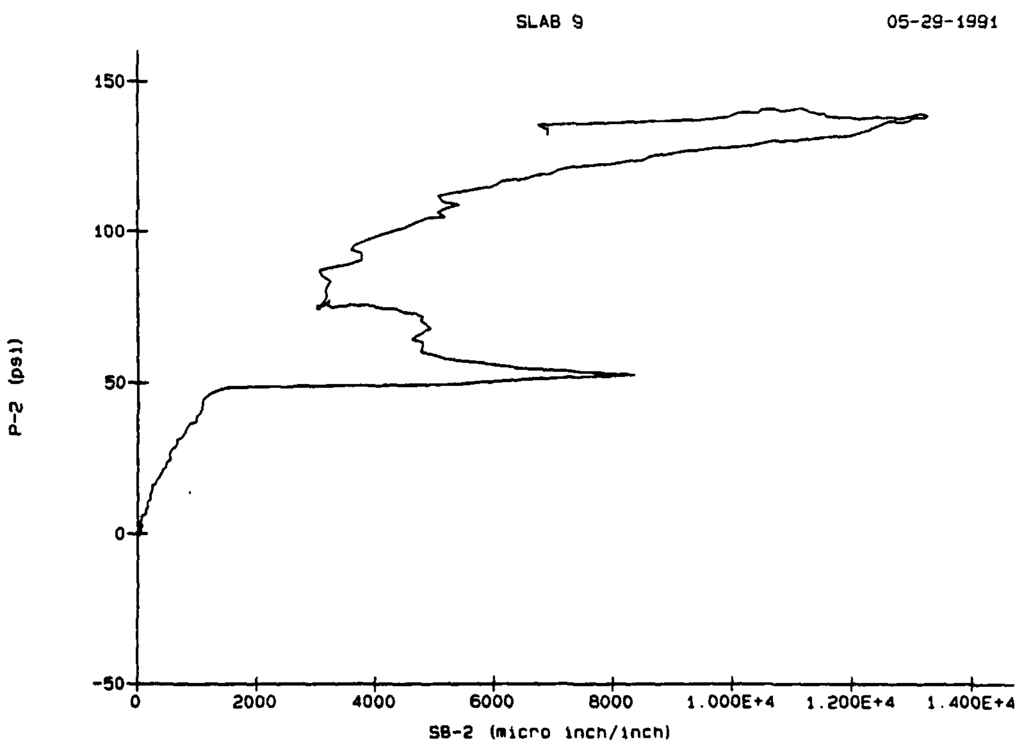

SLAB 9
05-29-1991
150
100
50
0
-50
P-2 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
D-1 (inches)


SLAB 9
05-29-1991
150
100
50
0
-50
P-2 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
D-2 (inches)

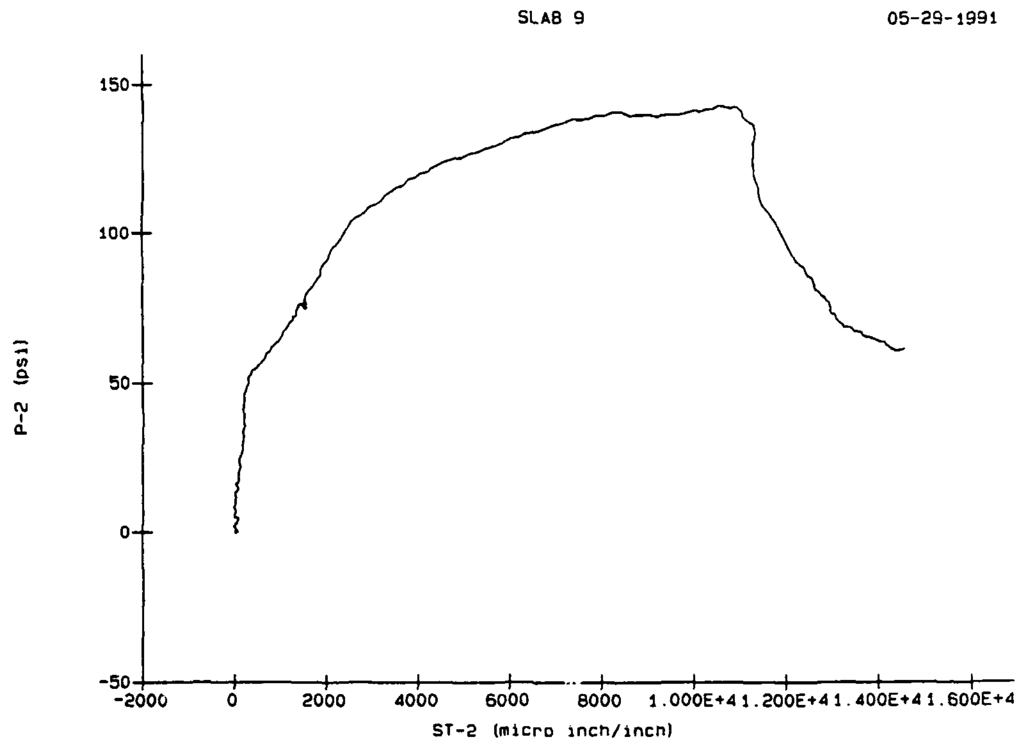

SLAB 9
05-29-1991
150
100
50
0
-50
P-2 (psi)
-5000
-4000
-3000
-2000
-1000
0
1000
SB-1 (micro inch/inch)

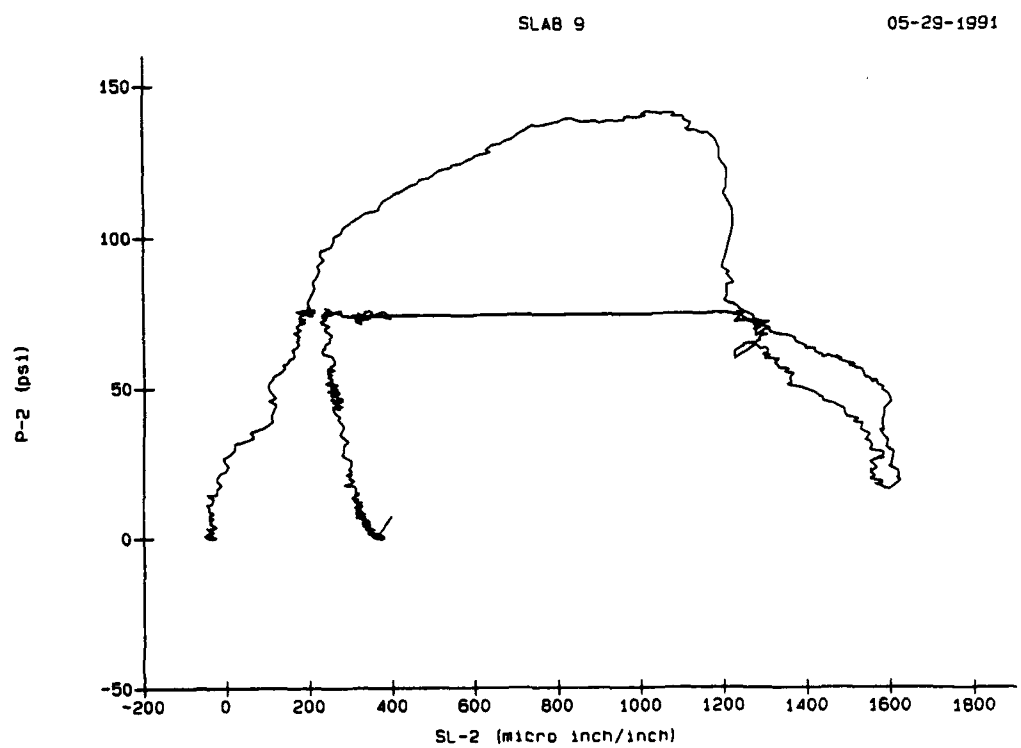


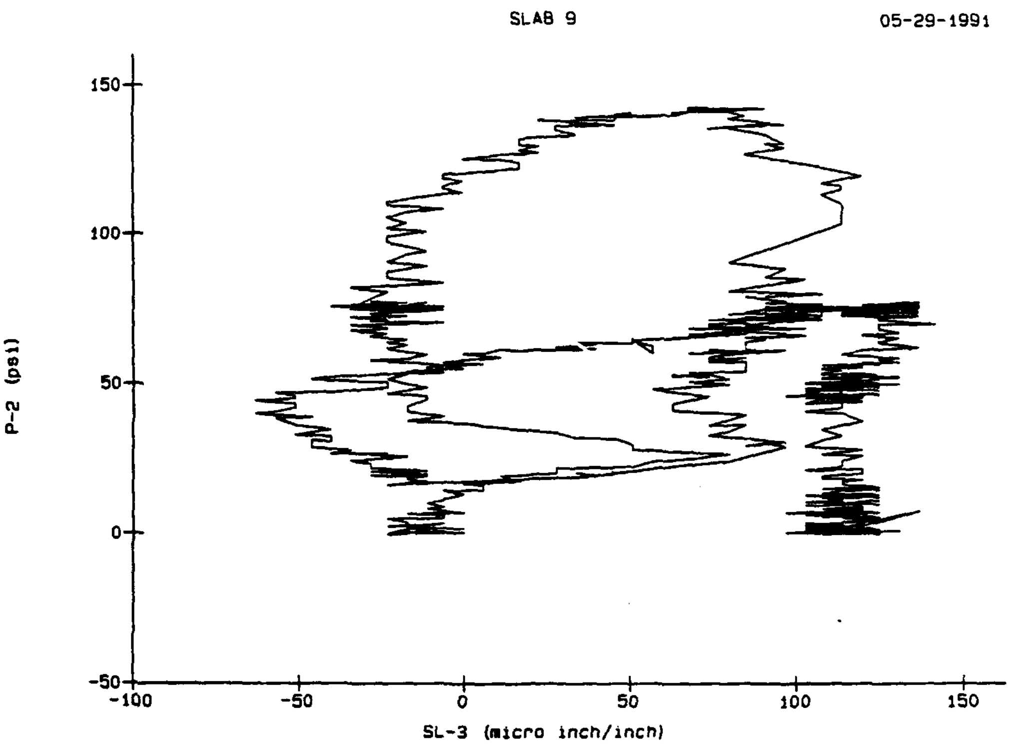
SLAB 9
05-29-1991
P-2 (psi)
150
100
50
0
-50
-500
0
500
1000
1500
2000
2500
3000
ST-1 (micro inch/inch)



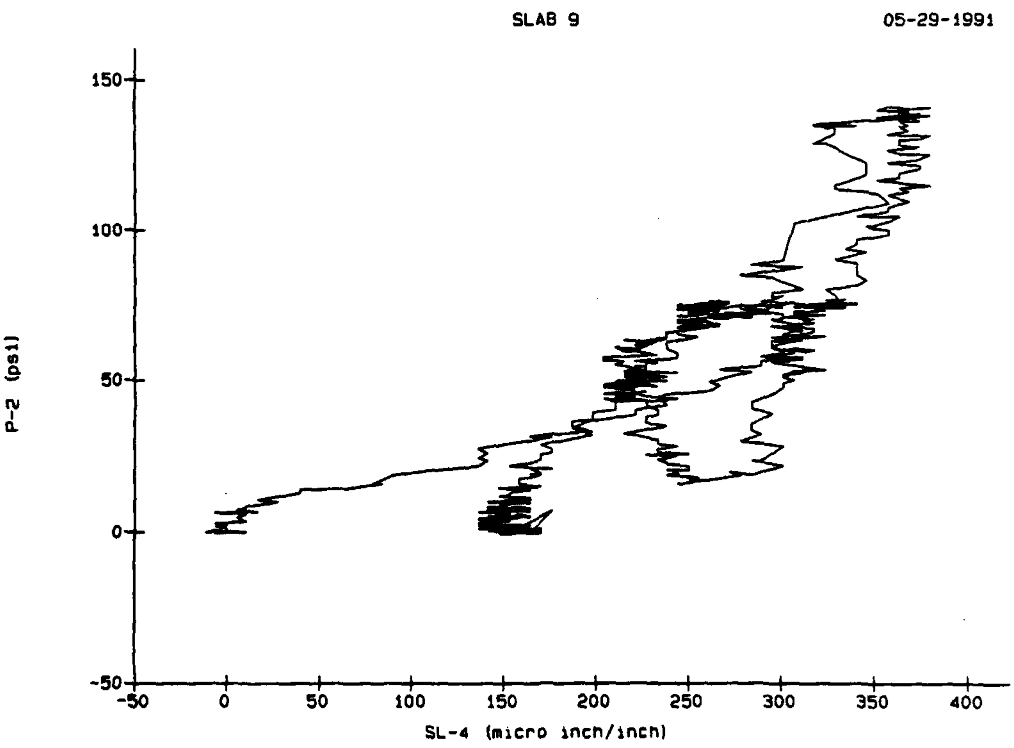
SLAB 9
05-29-1991
P-2 (psi)
150
100
50
0
-50
0
2000
4000
6000
8000
1.000E+4
1.200E+4
1.400E+4
SB-2 (micro inch/inch)


SLAB 9
05-29-1991
150
100
50
0
-50
P-2 (psi)
-2000
0
2000
4000
6000
8000
1.000E+4
1.200E+4
1.400E+4
1.600E+4
ST-2 (micro inch/inch)


SLAB 9
05-29-1991
150
100
50
0
-50
P-2 (psi)
-200
0
200
400
600
800
1000
1200
1400
1600
1800
SL-2 (micro inch/inch)

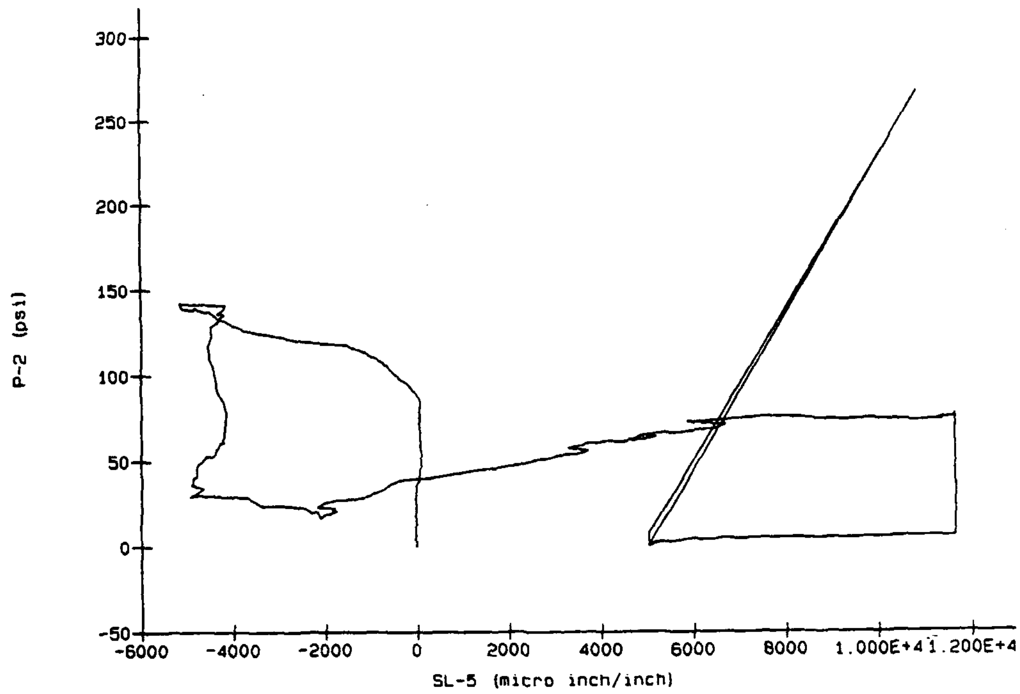


SLAB 9
05-29-1991
P-2 (psi)
SL-3 (micro inch/inch)
150
100
50
0
-50
-100
-50
0
50
100
150

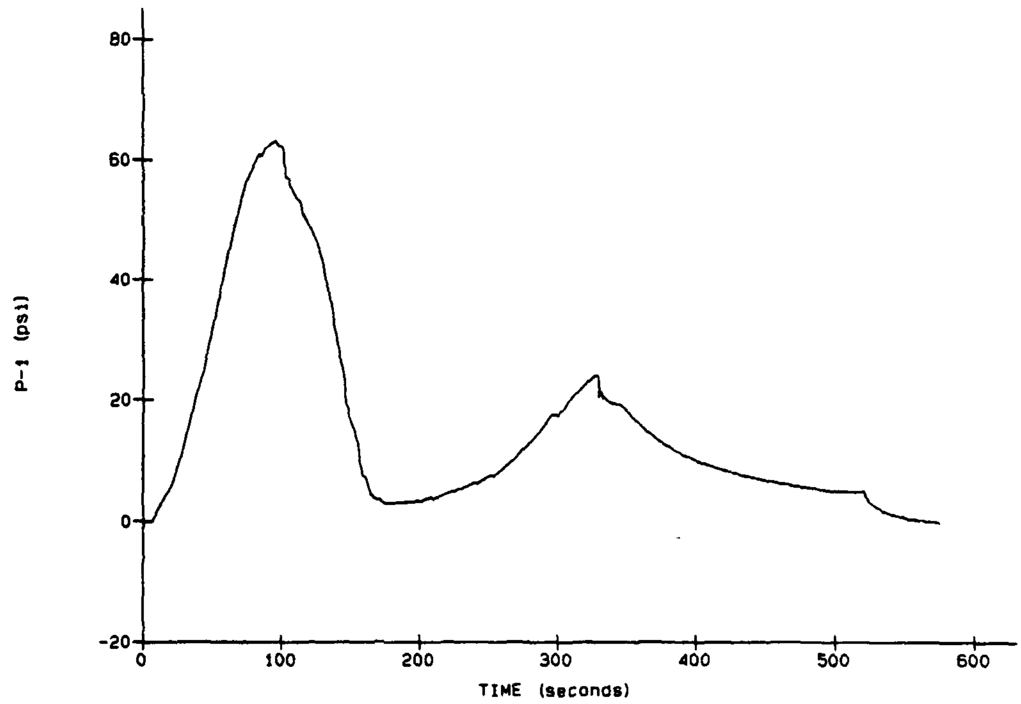


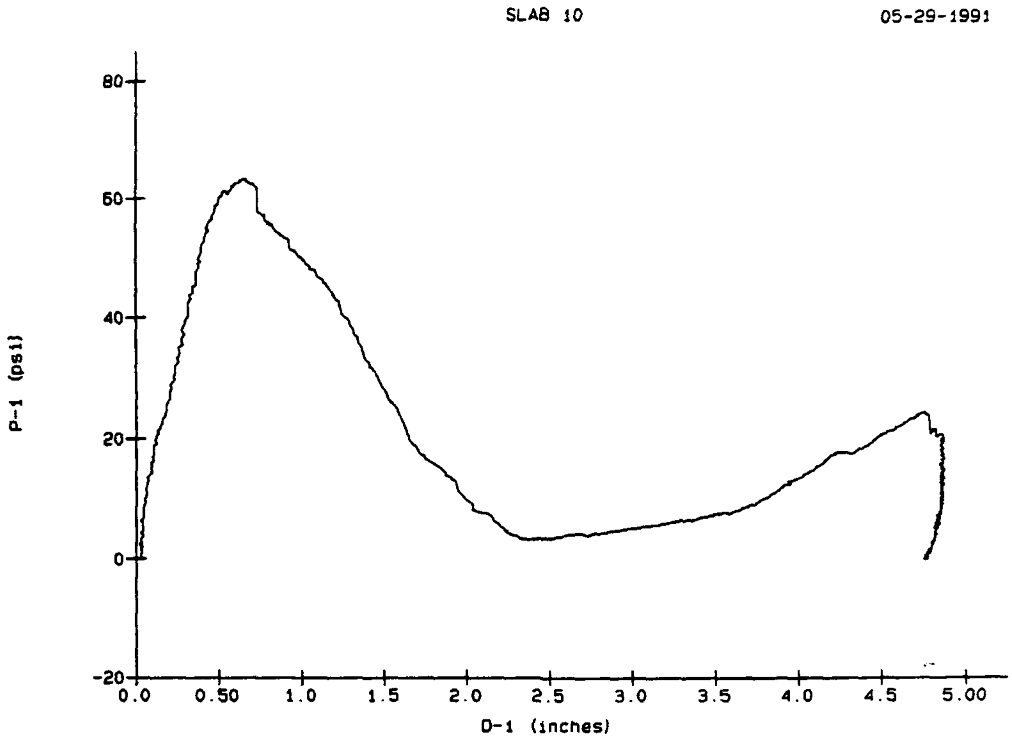
SLAB 9
05-29-1991
P-2 (psi)
SL-4 (micro inch/inch)
150
100
50
0
-50
-50
0
50
100
150
200
250
300
350
400

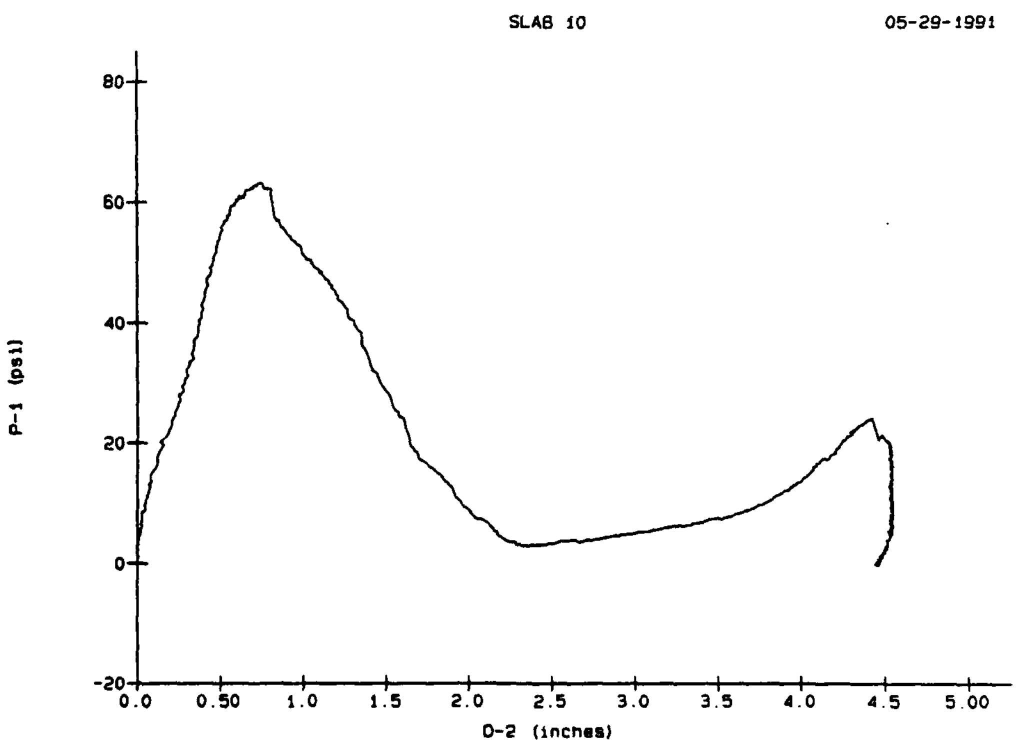
SLAB 9 05-29-1991



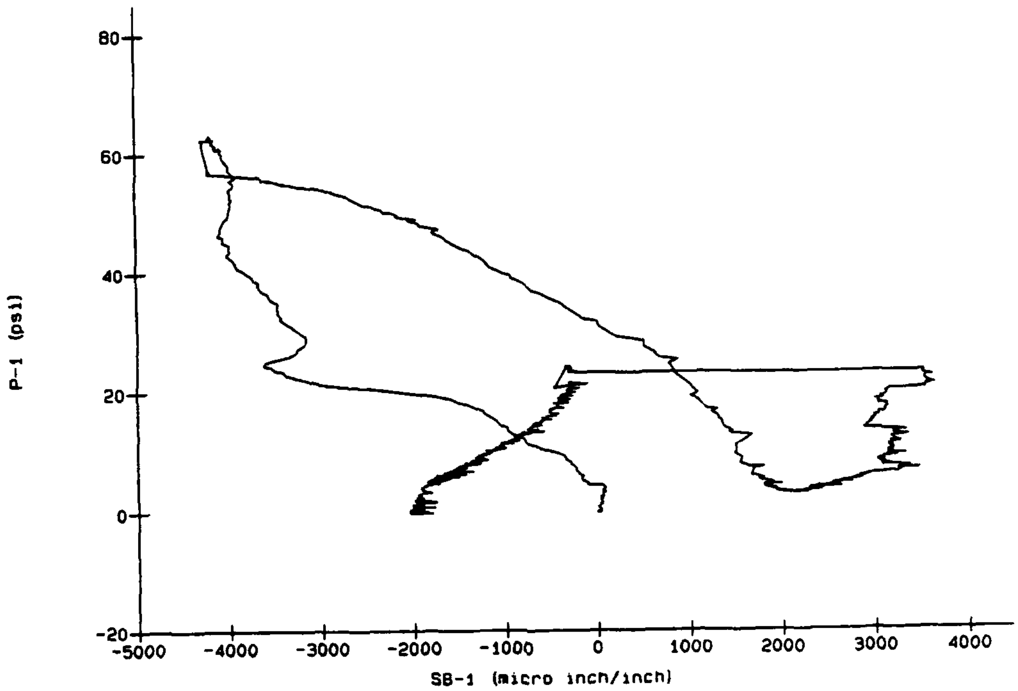
SLAB 10



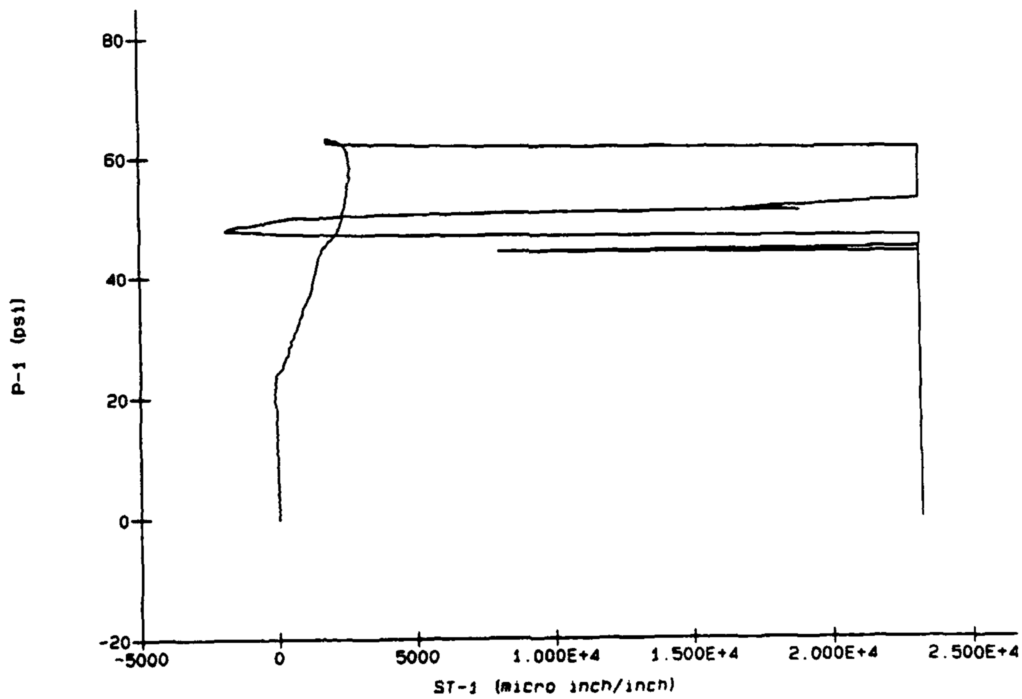

SLAB 10
05-29-1991
80
60
40
20
0
-20
P-1 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.00
D-1 (inches)

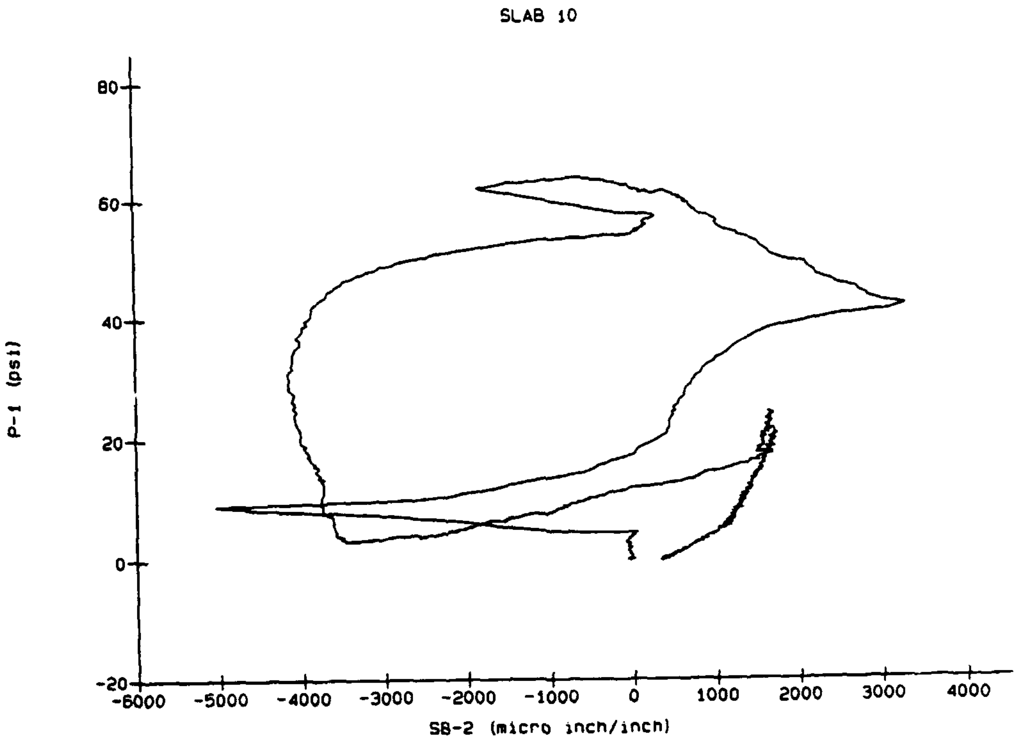

SLAB 10
05-29-1991
80
60
40
20
0
-20
P-1 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.00
D-2 (inches)

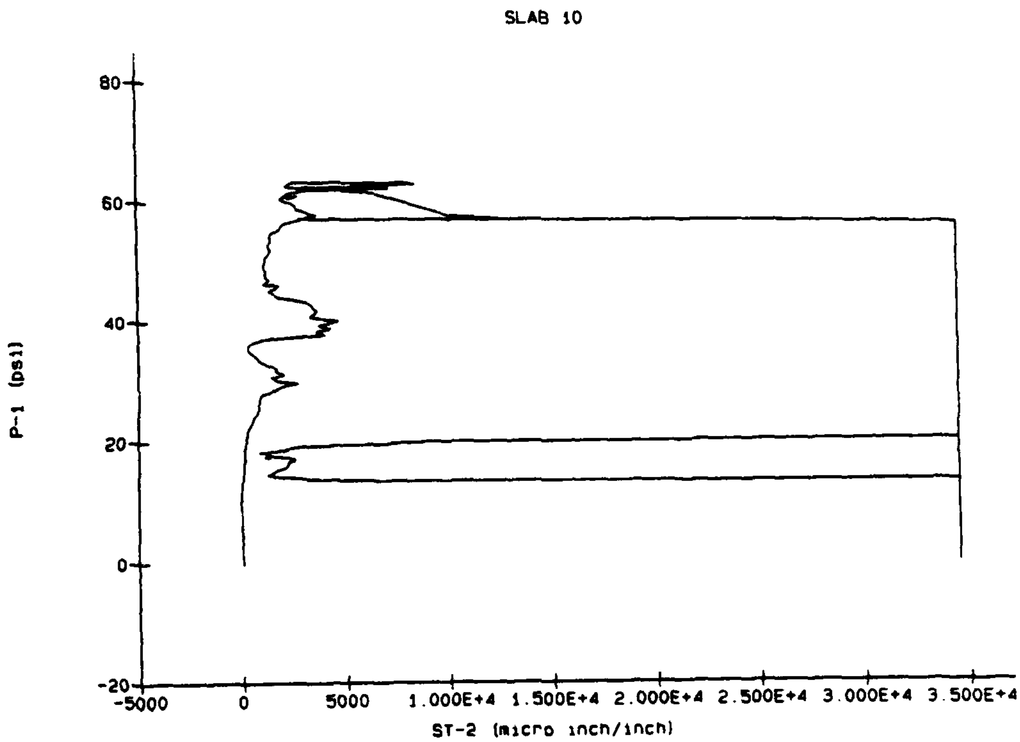
SLAB 10



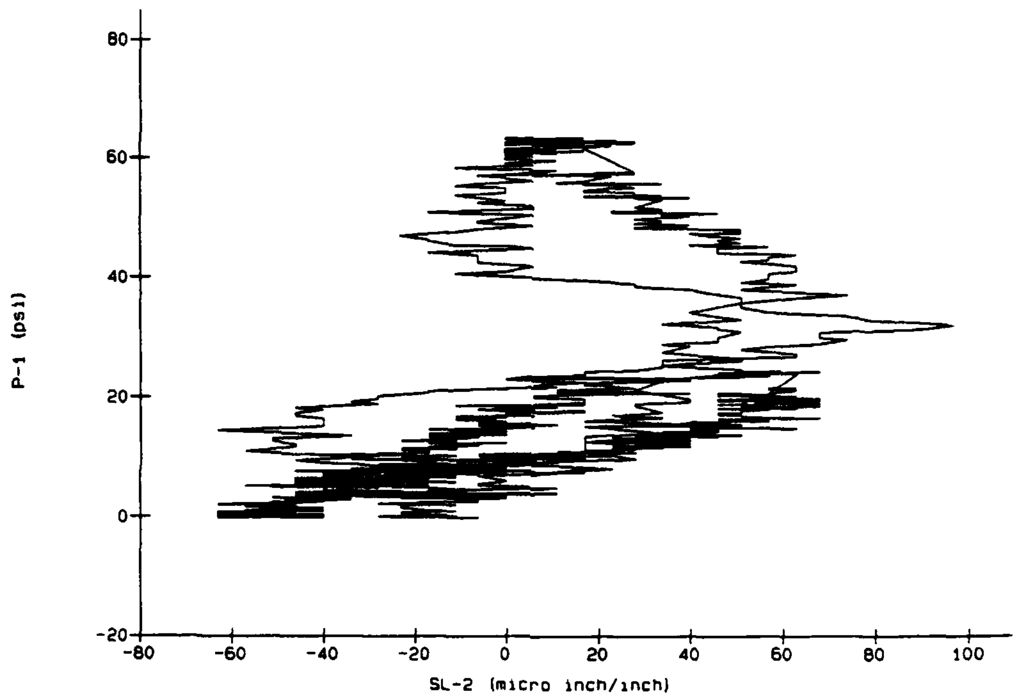
SLAB 10



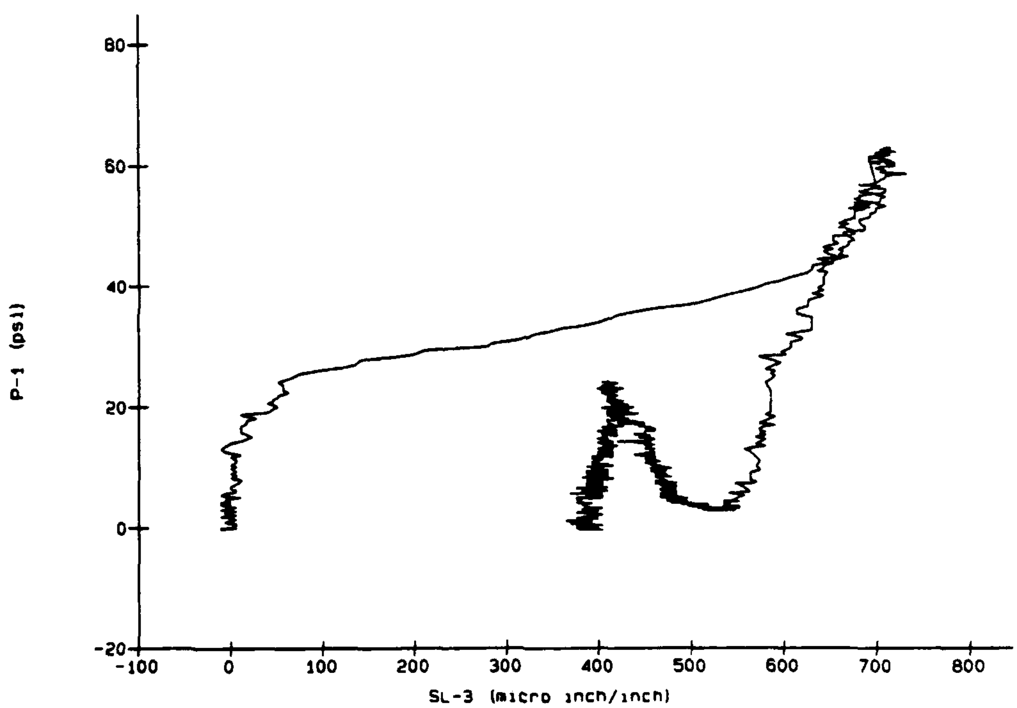

SLAB 10
P-1 (psi)
80
60
40
20
0
-20
-6000
-5000
-4000
-3000
-2000
-1000
0
1000
2000
3000
4000
SB-2 (micro inch/inch)


SLAB 10
P-1 (psi)
80
60
40
20
0
-20
-5000
0
5000
1.000E+4
1.500E+4
2.000E+4
2.500E+4
3.000E+4
3.500E+4
ST-2 (micro inch/inch)

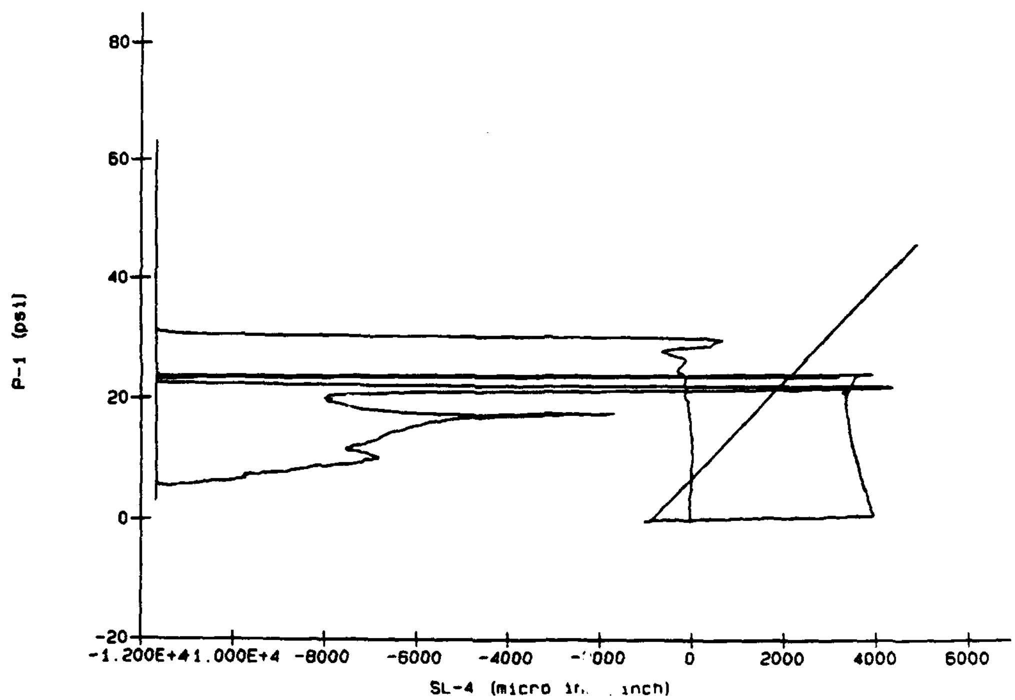
SLAB 10



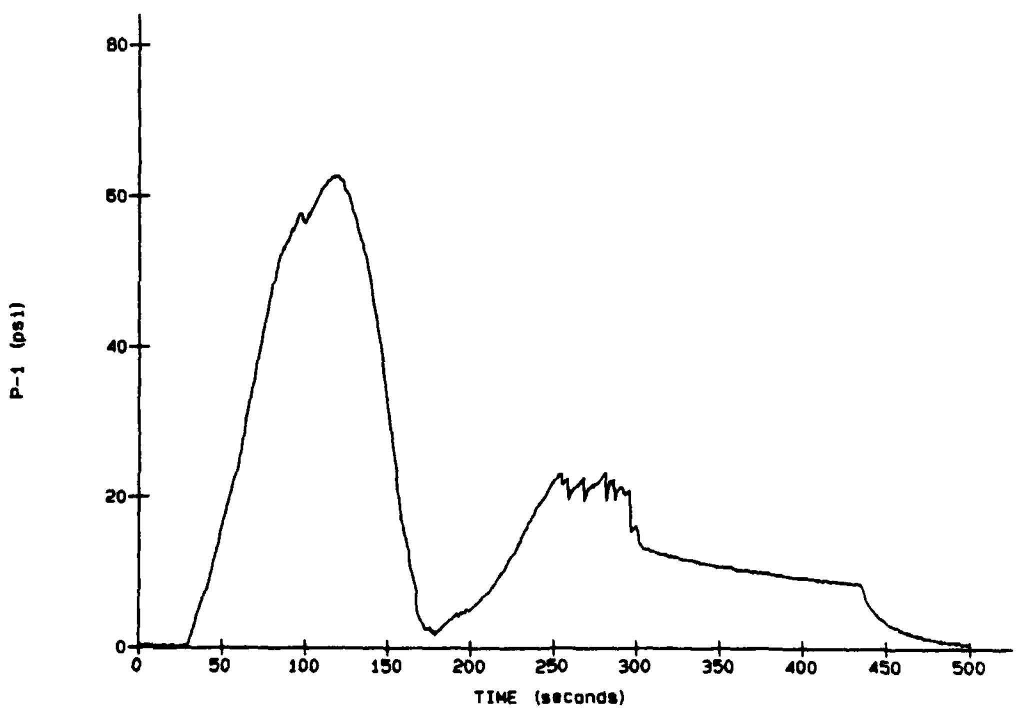
SLAB 10



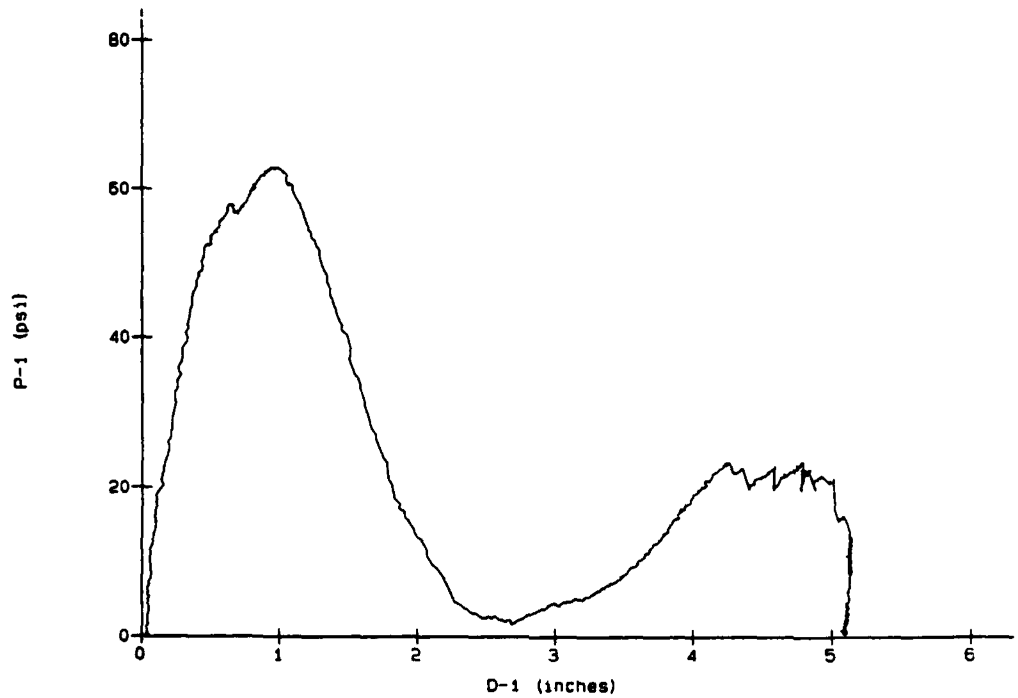
SLAB 10



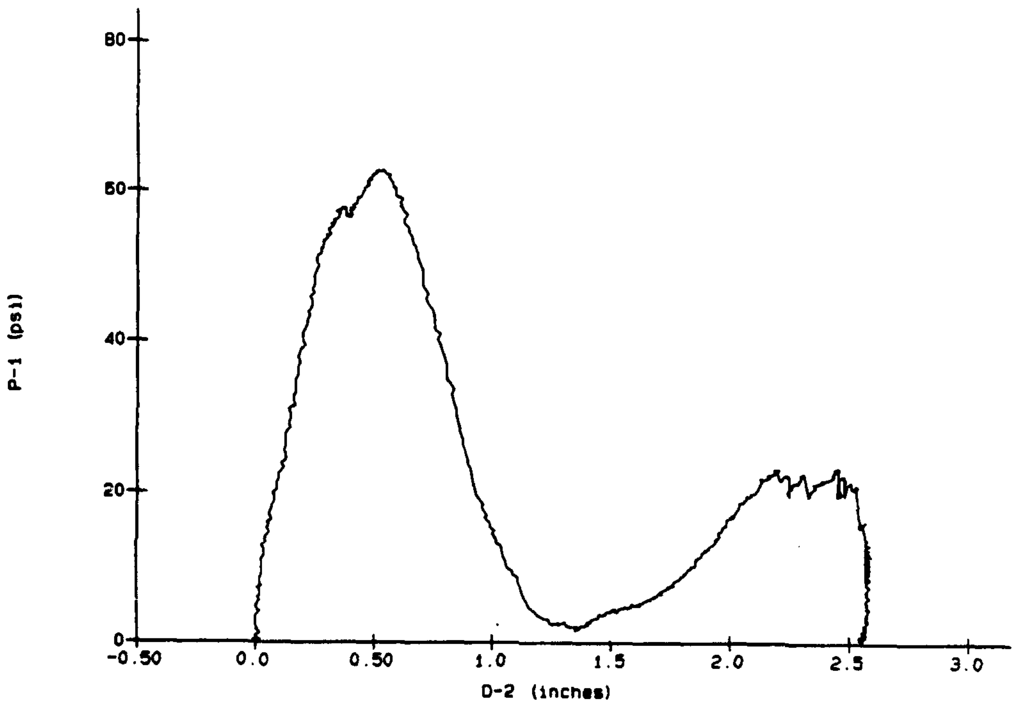
SLAB 11

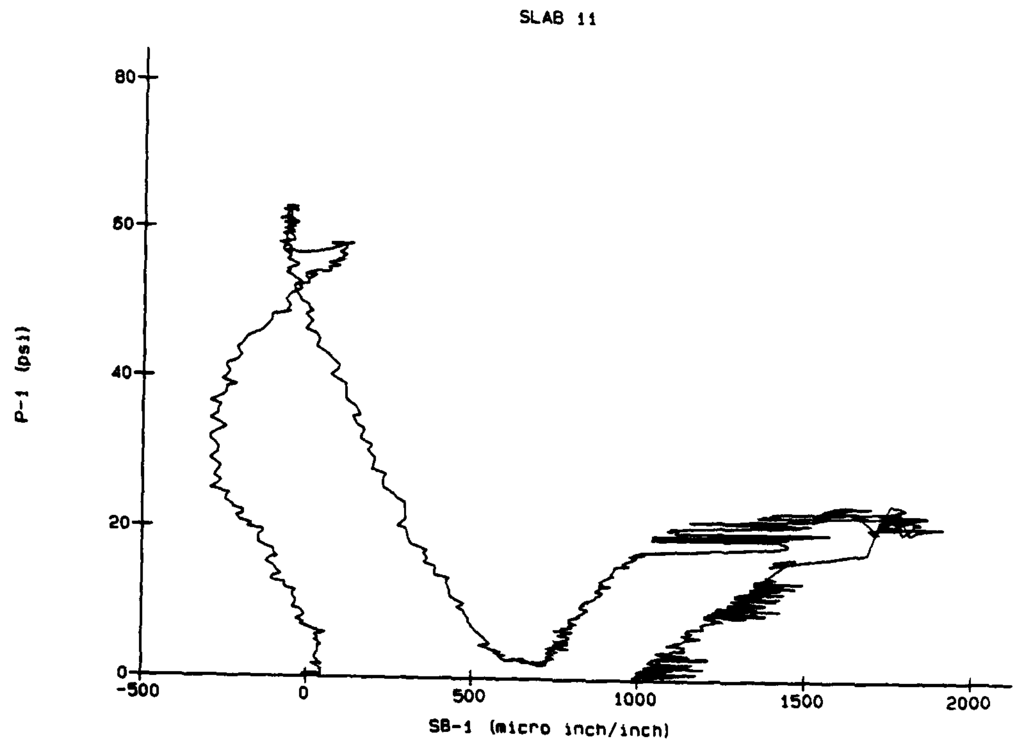


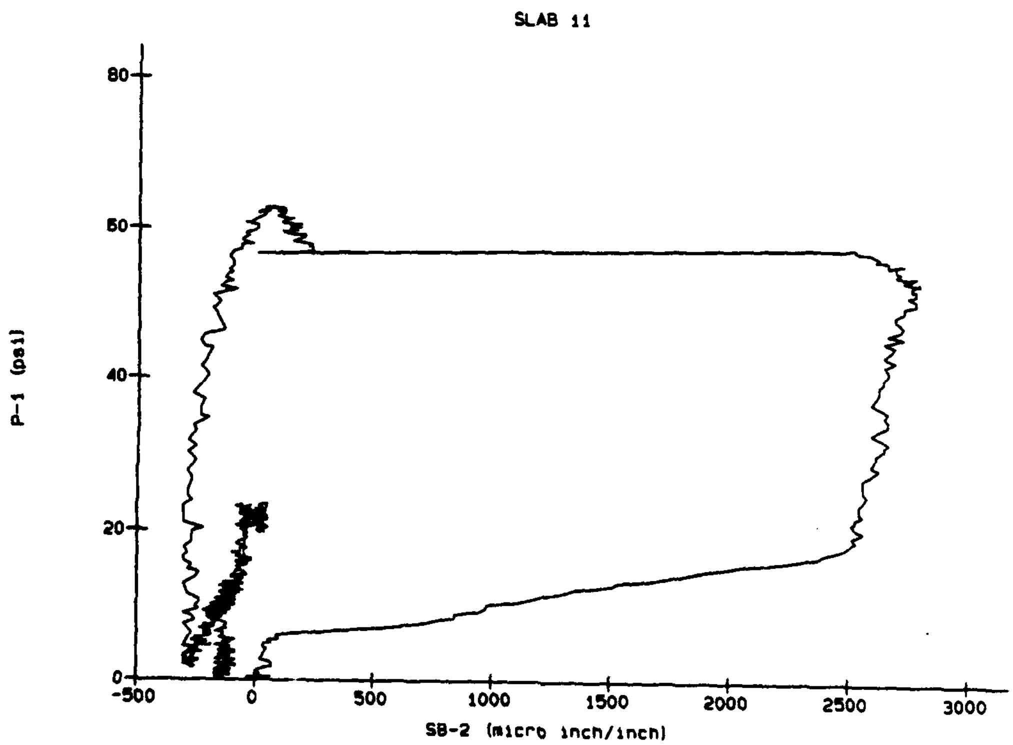
SLAB 11

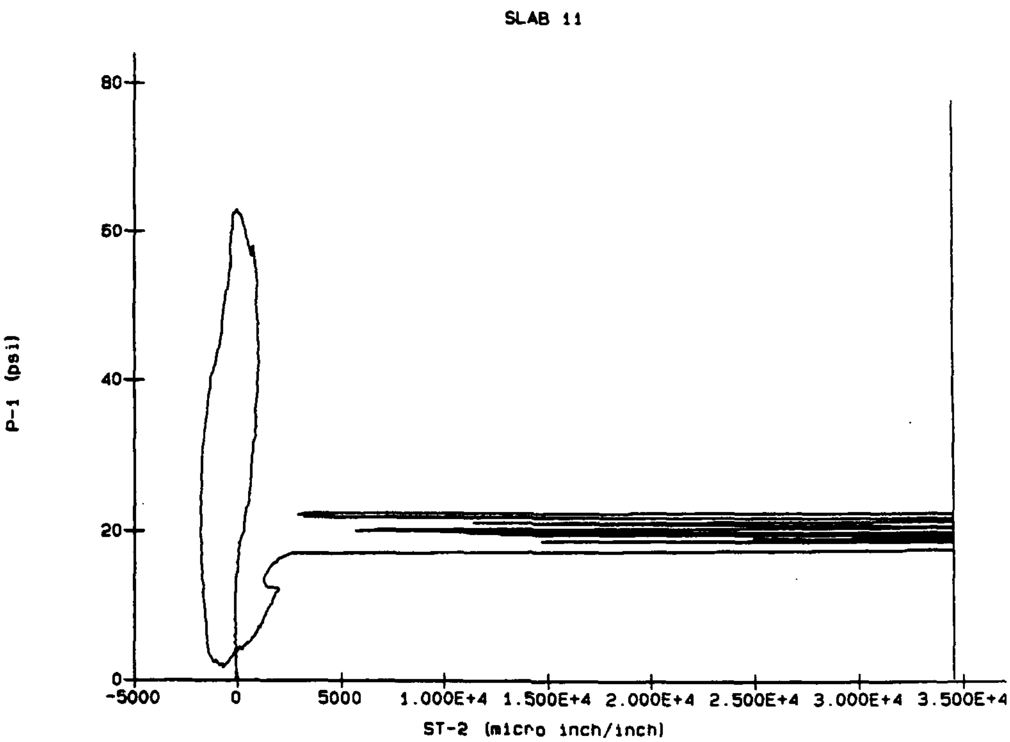


SLAB 11

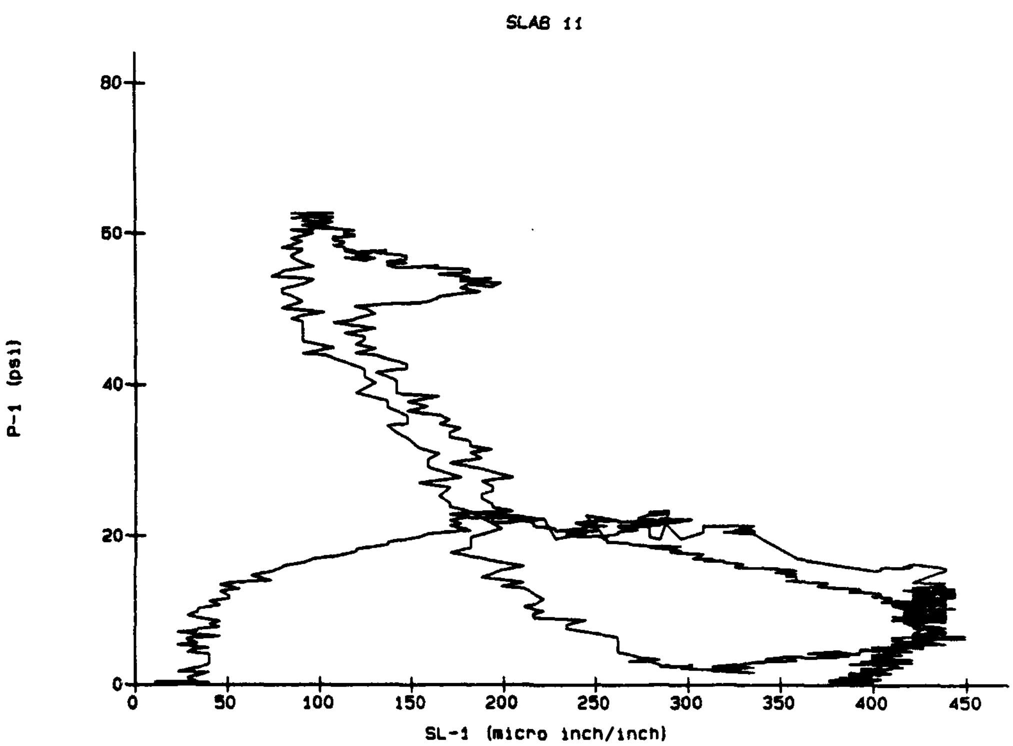



SLAB 11
P-1 (psi)
0
20
40
60
80
-500
0
500
1000
1500
2000
SB-1 (micro inch/inch)

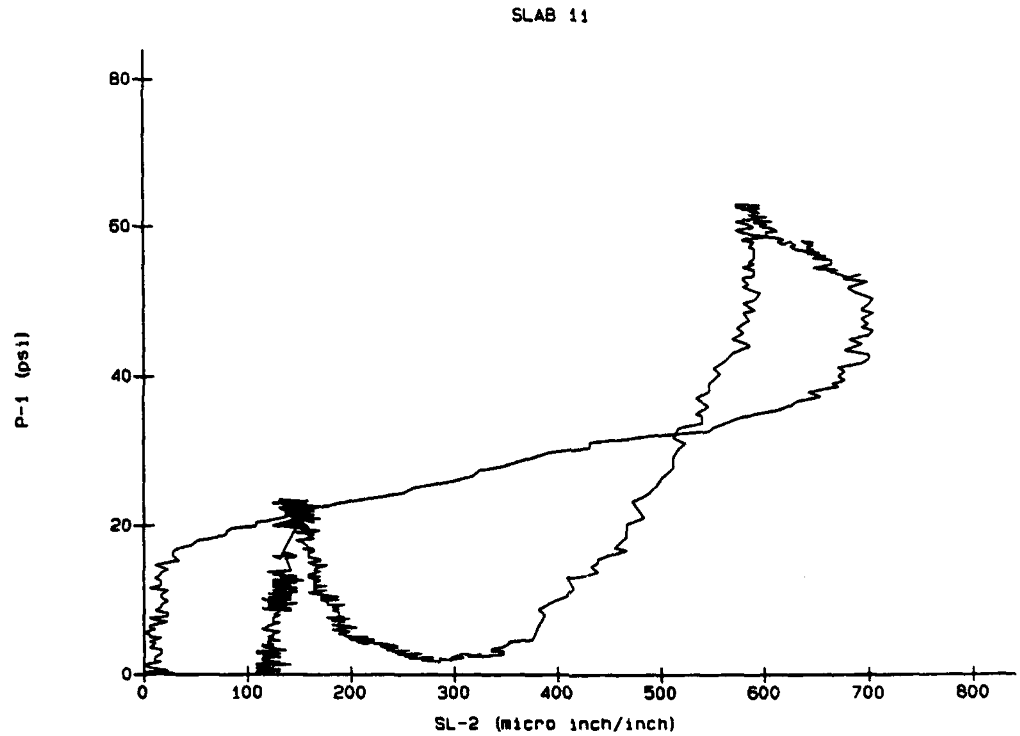

SLAB 11
P-1 (psi)
0
20
40
60
80
-500
0
500
1000
1500
2000
2500
3000
SB-2 (micro inch/inch)

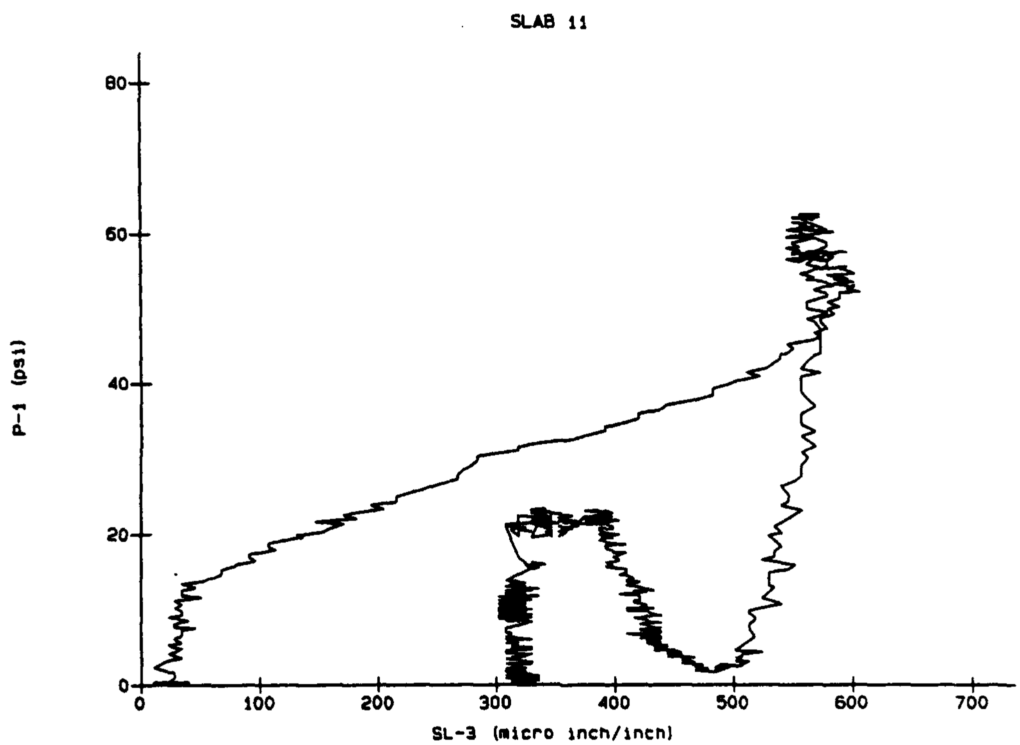


SLAB 11
80
60
40
20
0
P-1 (psi)
-5000
0
5000
1.000E+4
1.500E+4
2.000E+4
2.500E+4
3.000E+4
3.500E+4
ST-2 (micro inch/inch)

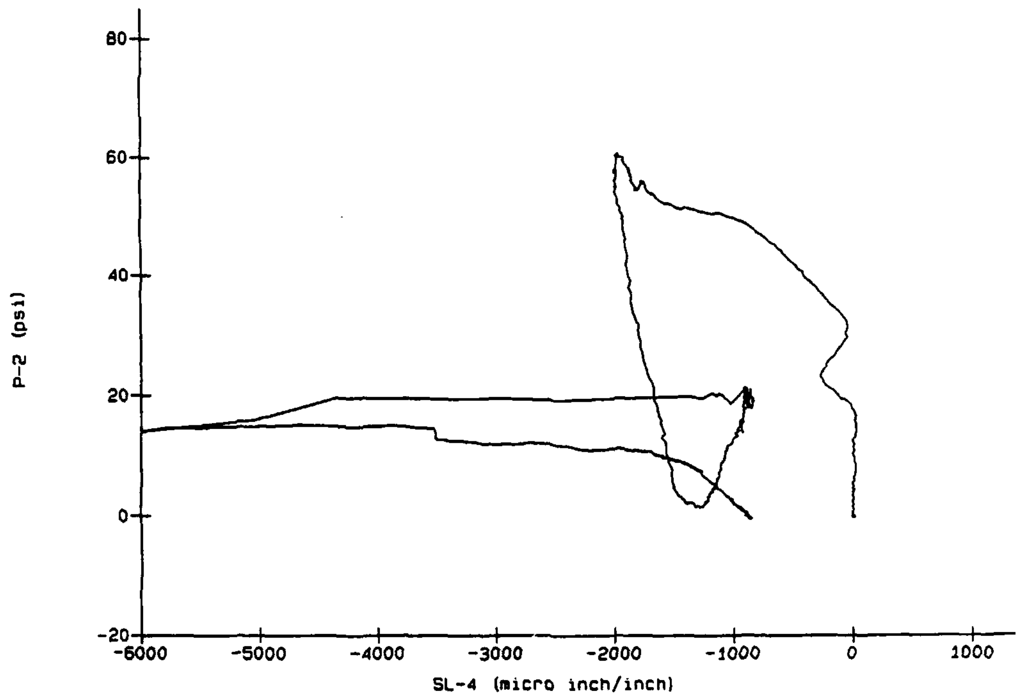


SLAB 11
80
60
40
20
0
P-1 (psi)
0
50
100
150
200
250
300
350
400
450
SL-1 (micro inch/inch)

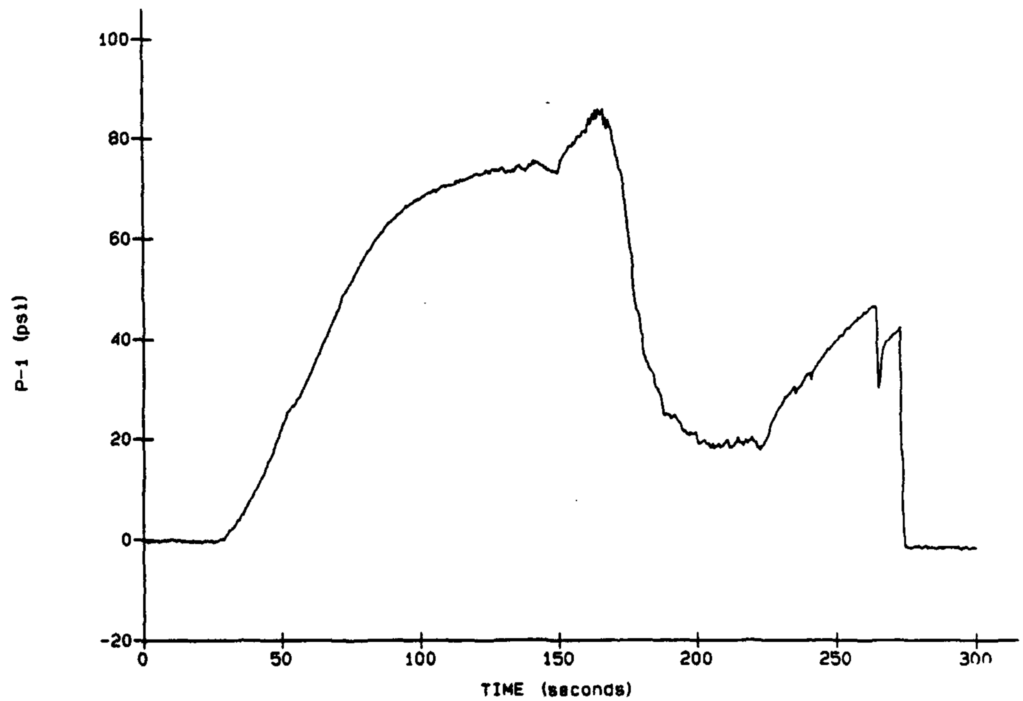

SLAB 11
P-1 (psi)
0
20
40
60
80
0
100
200
300
400
500
600
700
800
SL-2 (micro inch/inch)

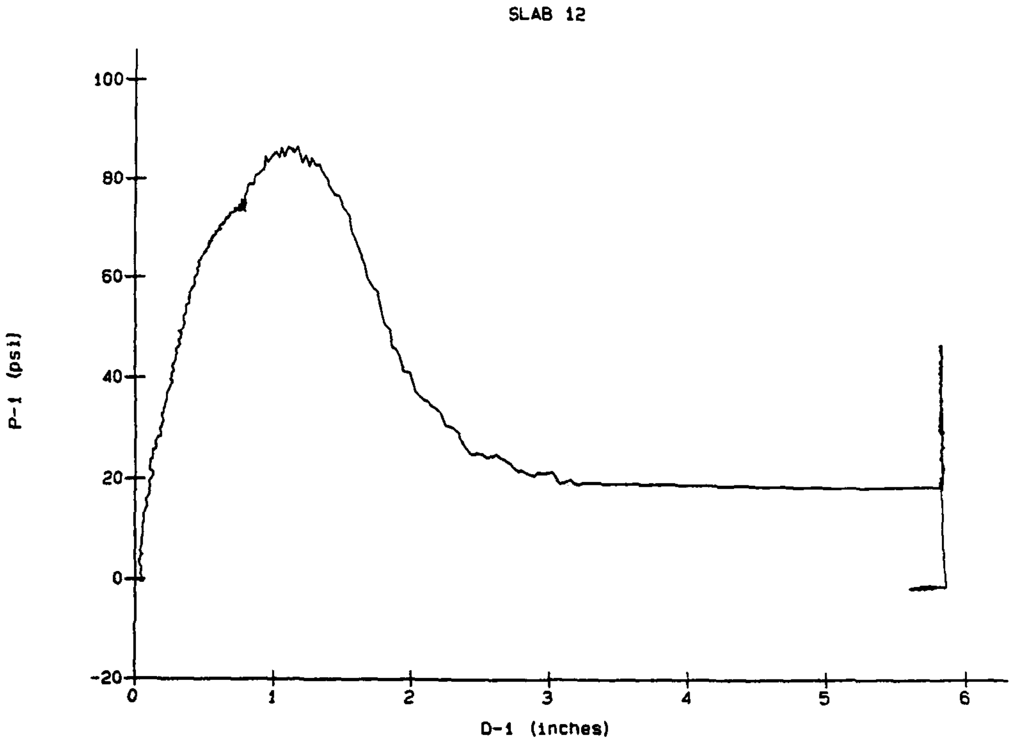

SLAB 11
P-1 (psi)
0
20
40
60
80
0
100
200
300
400
500
600
700
SL-3 (micro inch/inch)

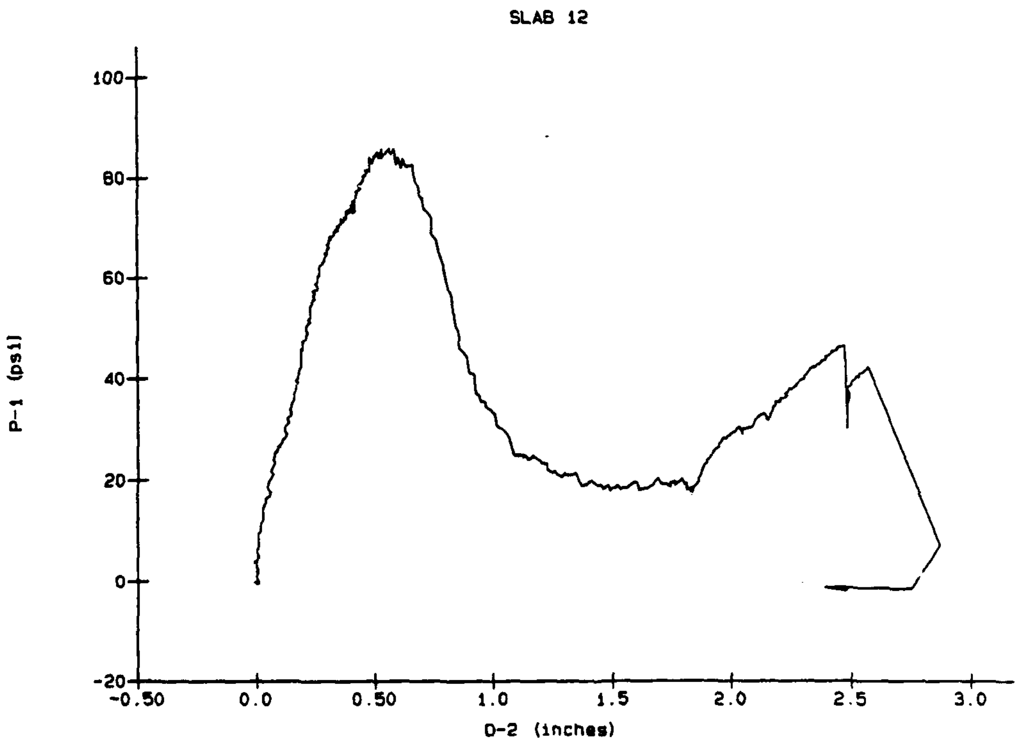
SLAB 11



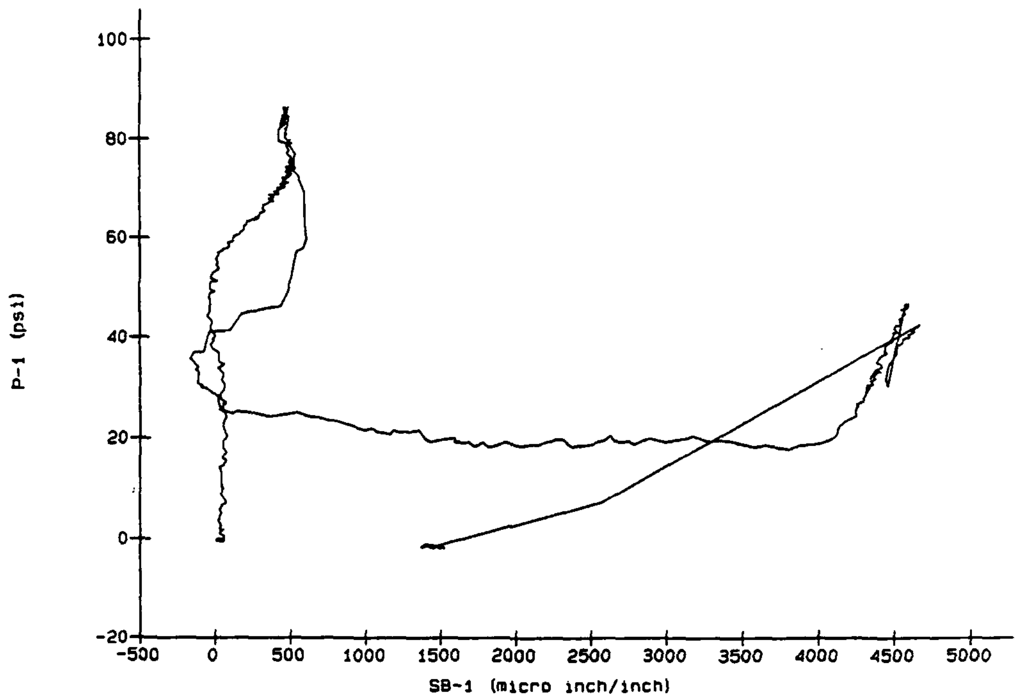
SLAB 12



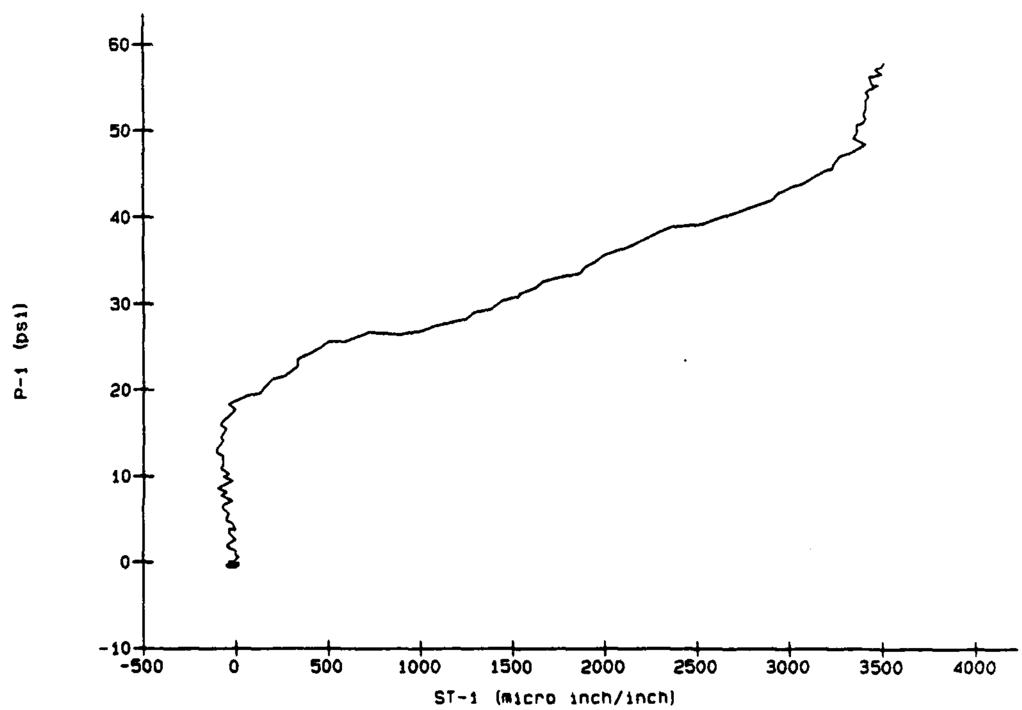

SLAB 12
P-1 (psi)
100
80
60
40
20
0
-20
0
1
2
3
4
5
6
D-1 (inches)


SLAB 12
P-1 (psi)
100
80
60
40
20
0
-20
-0.50
0.0
0.50
1.0
1.5
2.0
2.5
3.0
D-2 (inches)

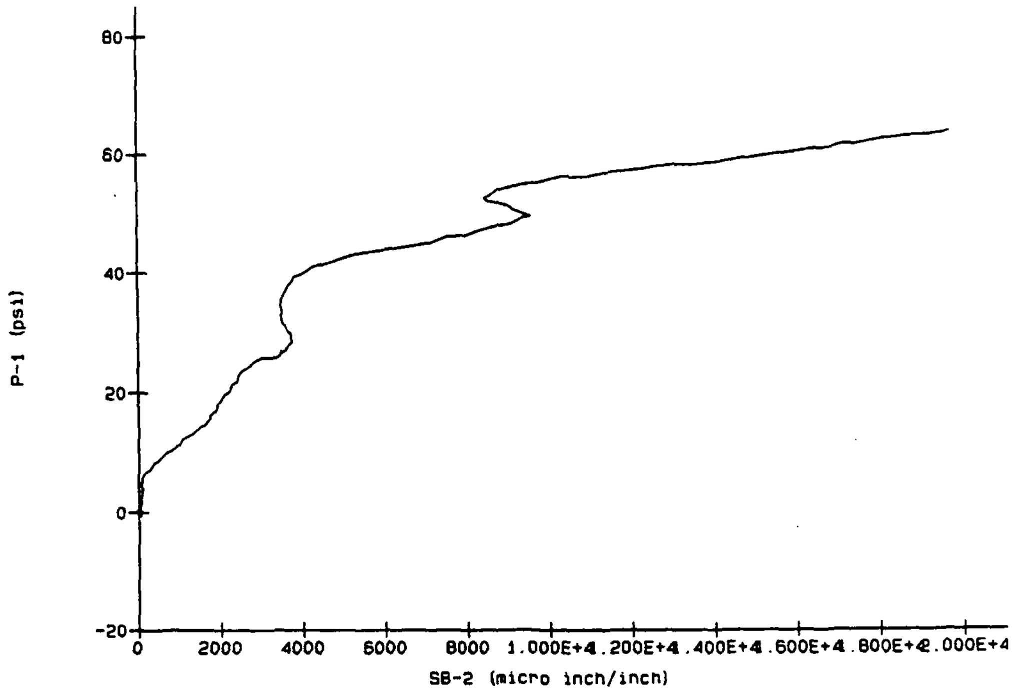
SLAB 12



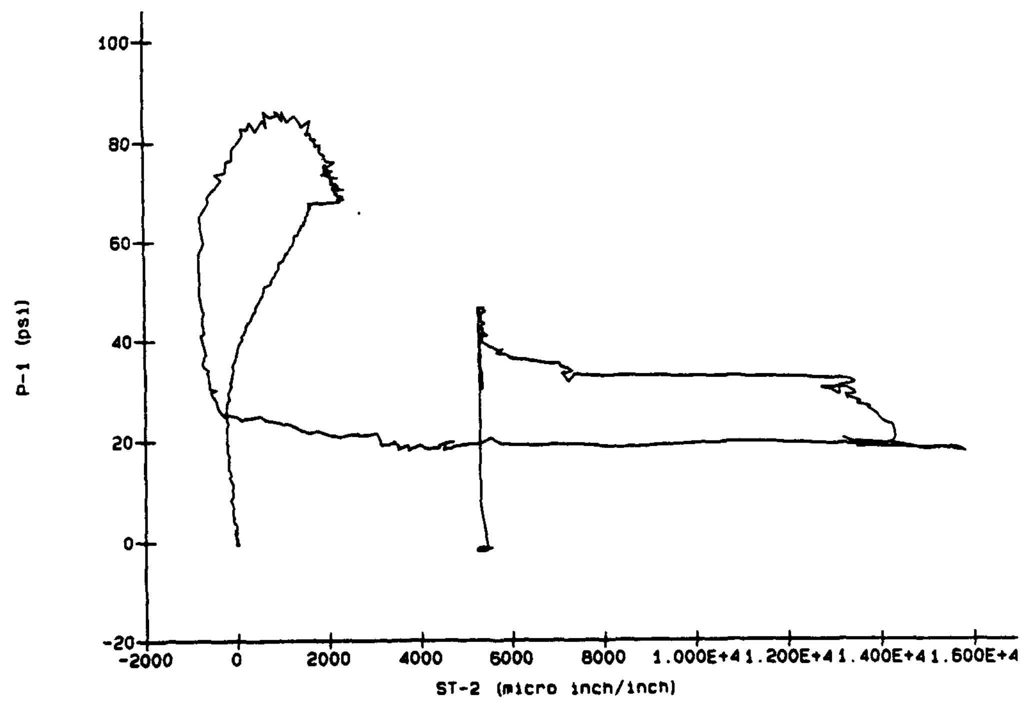
SLAB 12



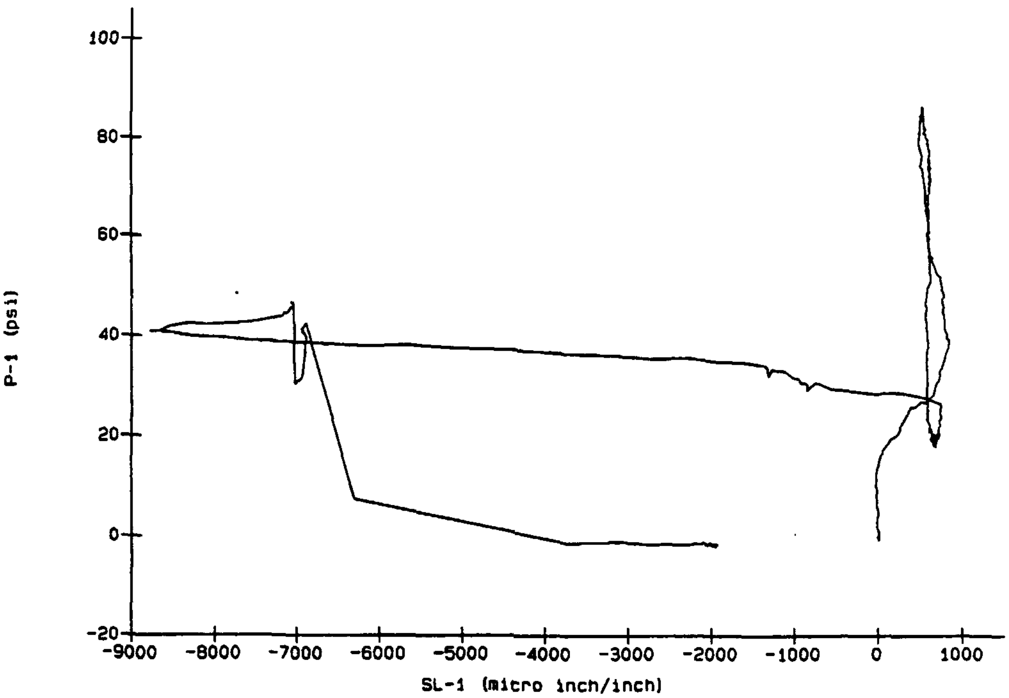
SLAB 12



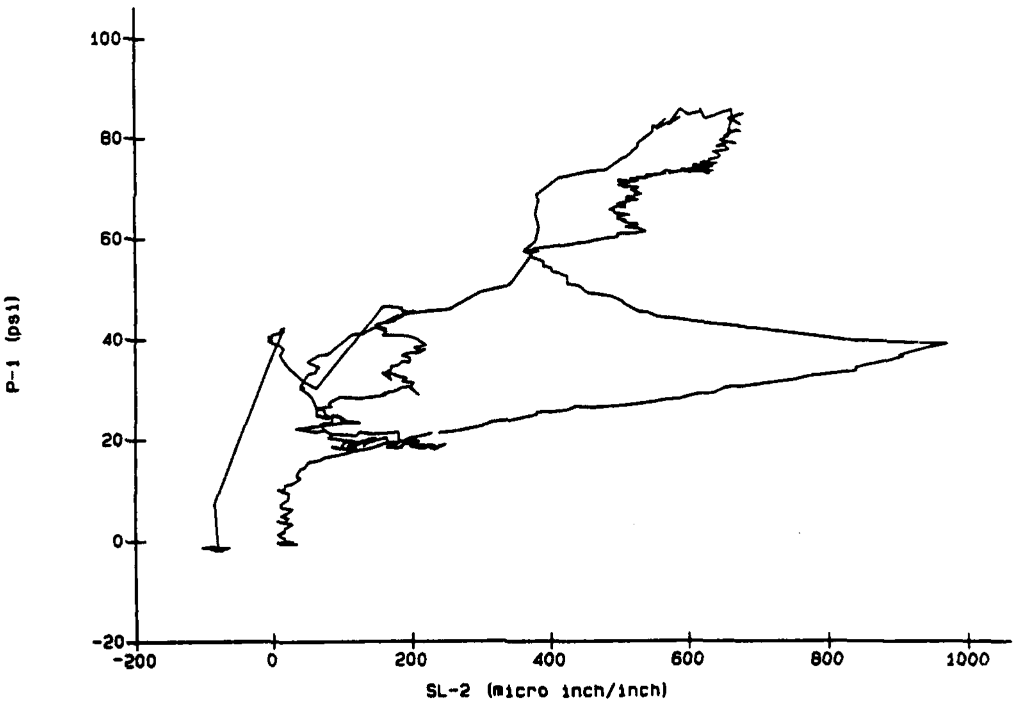
SLAB 12

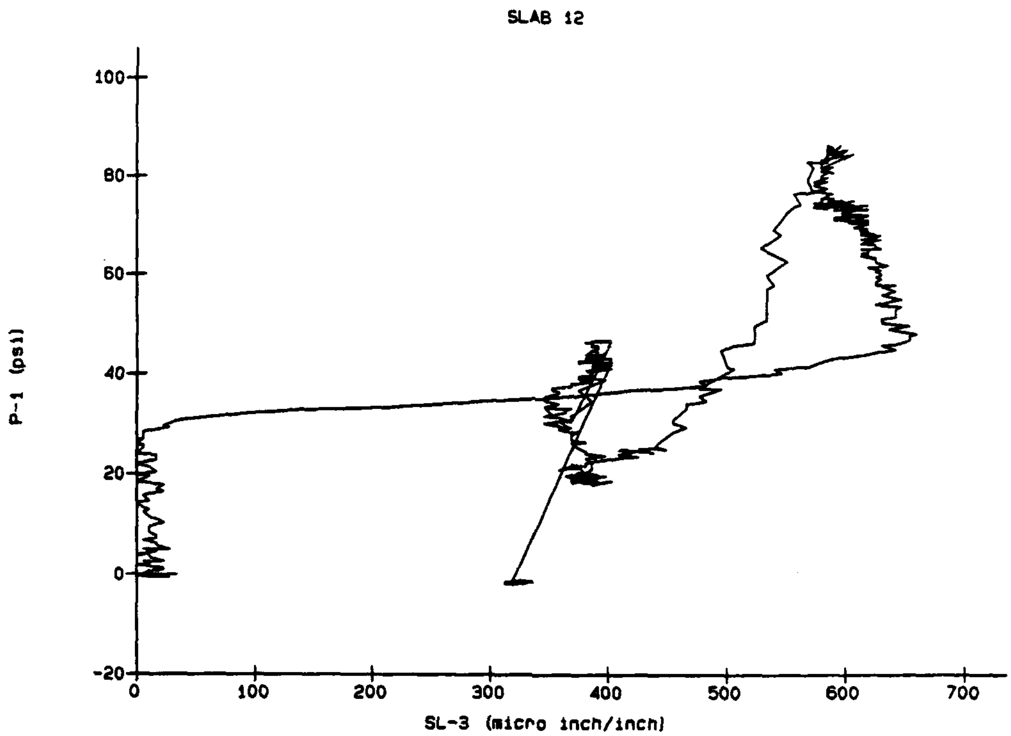


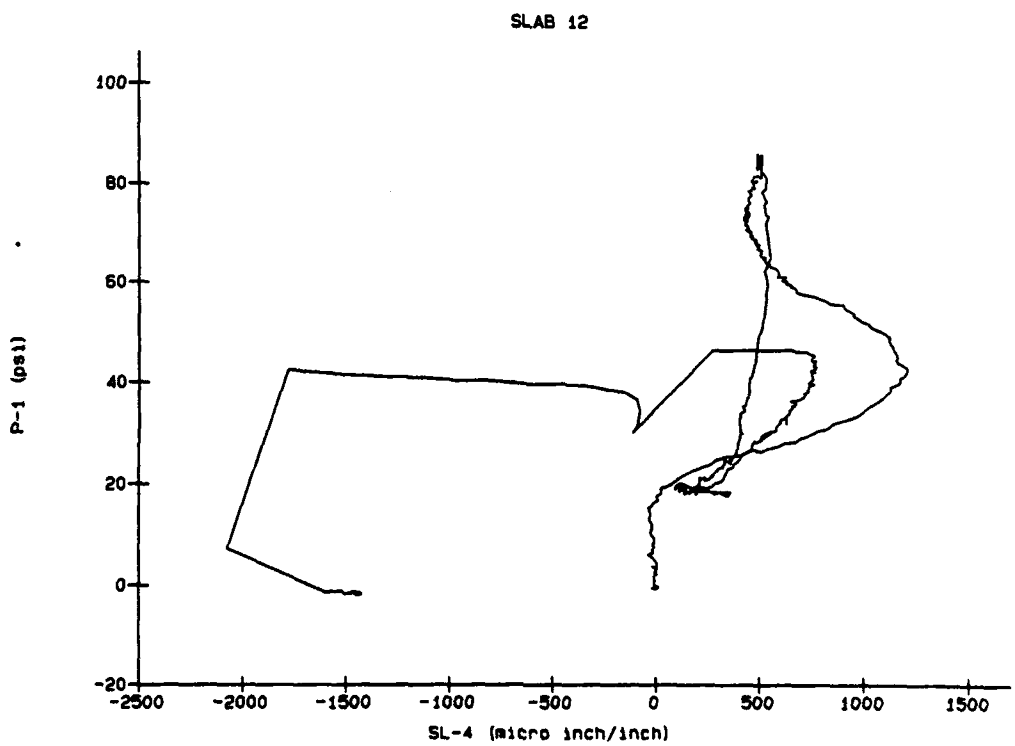
SLAB 12



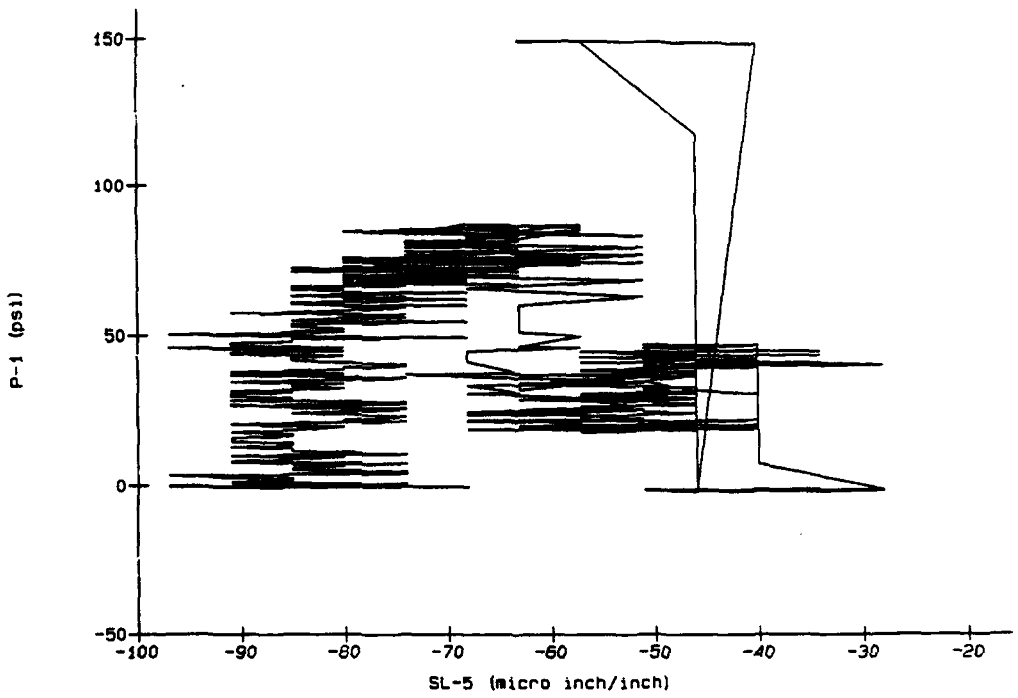
SLAB 12



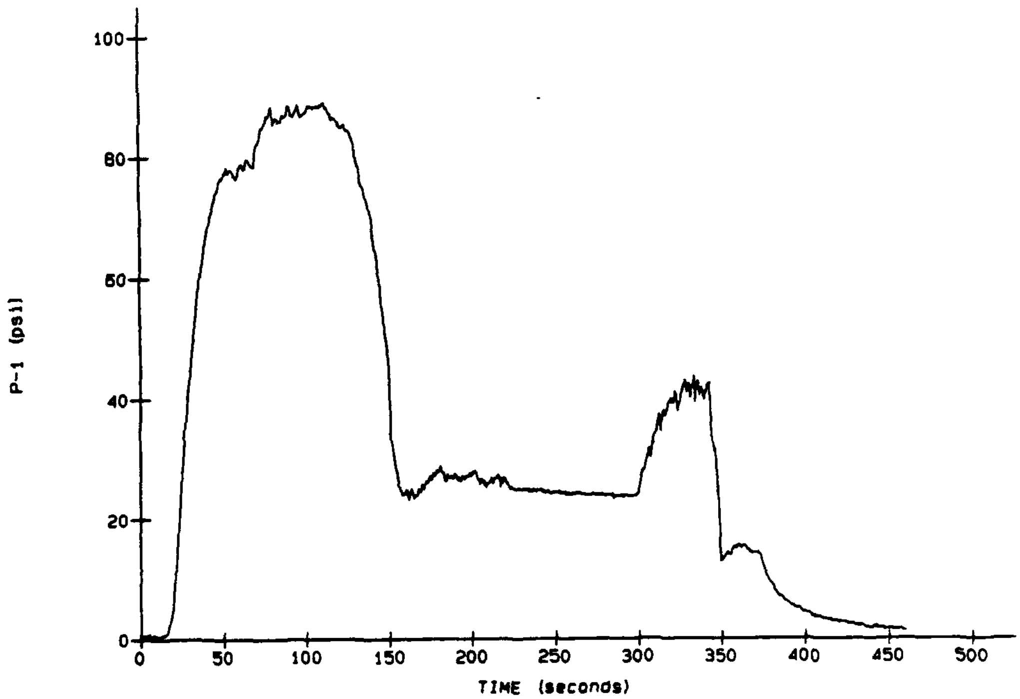

SLAB 12
P-1 (psi)
100
80
60
40
20
0
-20
0
100
200
300
400
500
600
700
SL-3 (micro inch/inch)


SLAB 12
P-1 (psi)
100
80
60
40
20
0
-20
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
SL-4 (micro inch/inch)

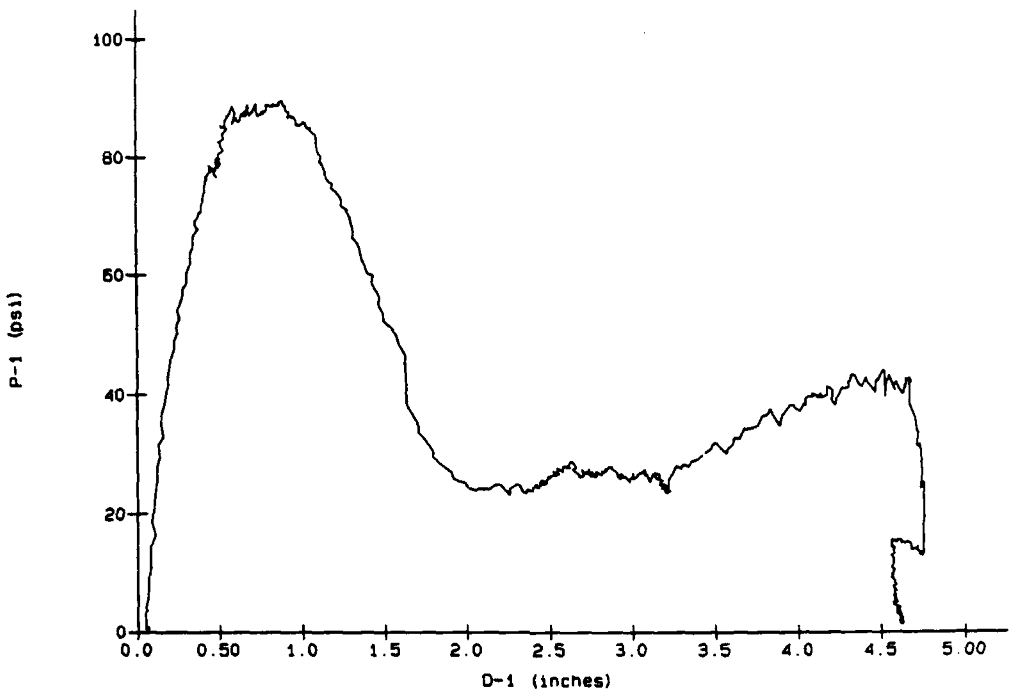
SLAB 12



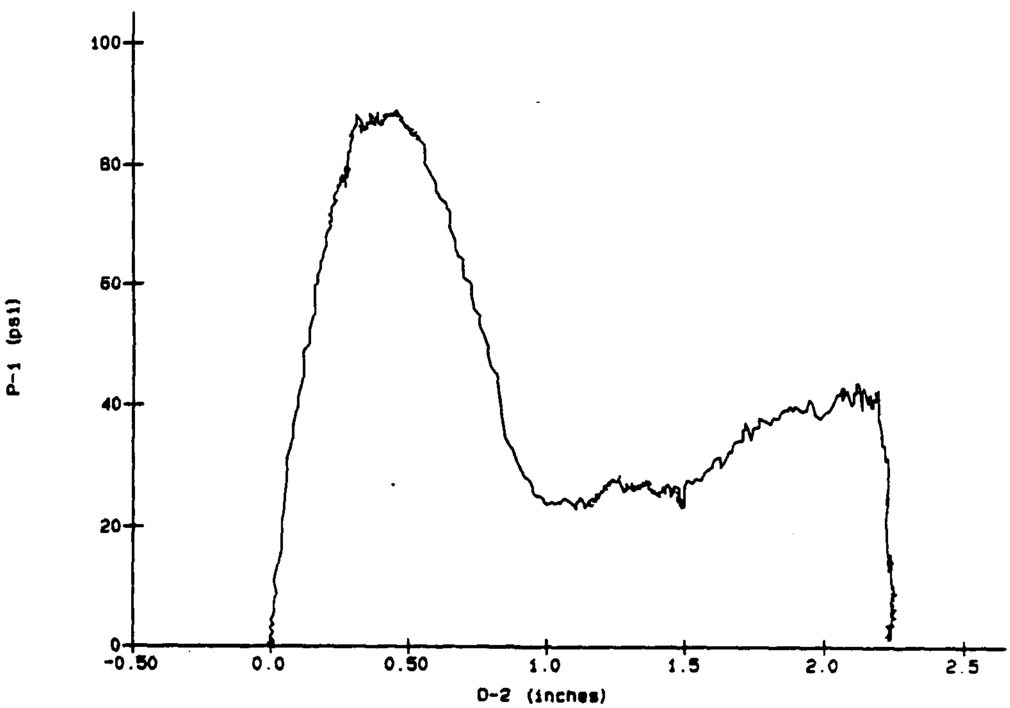
SLAB 13

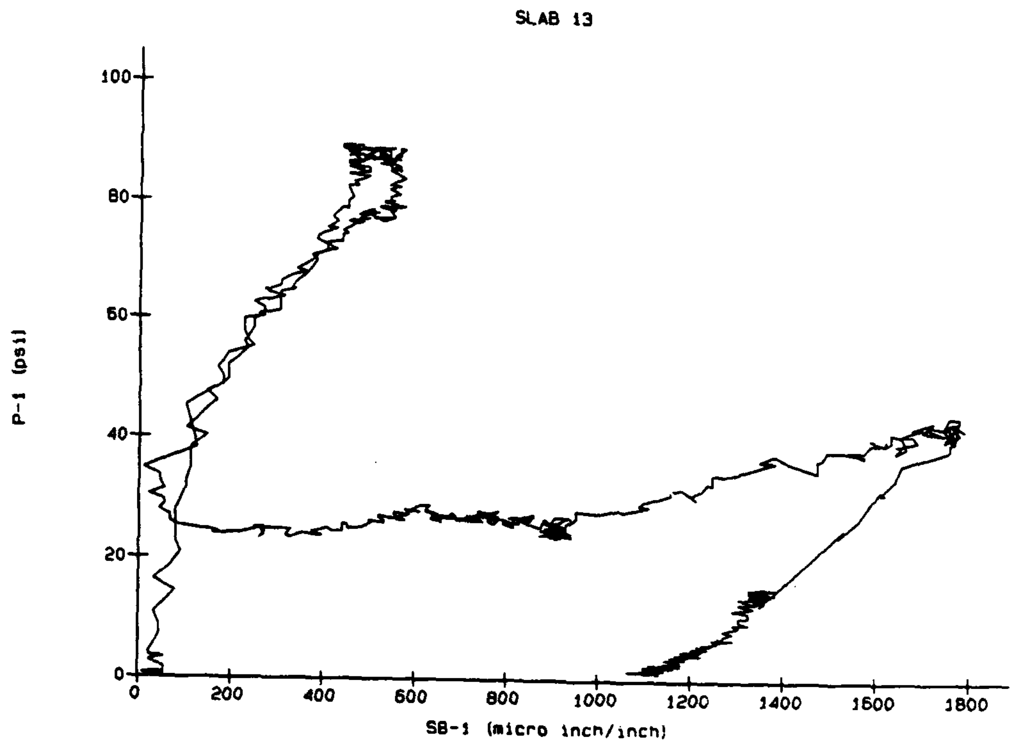


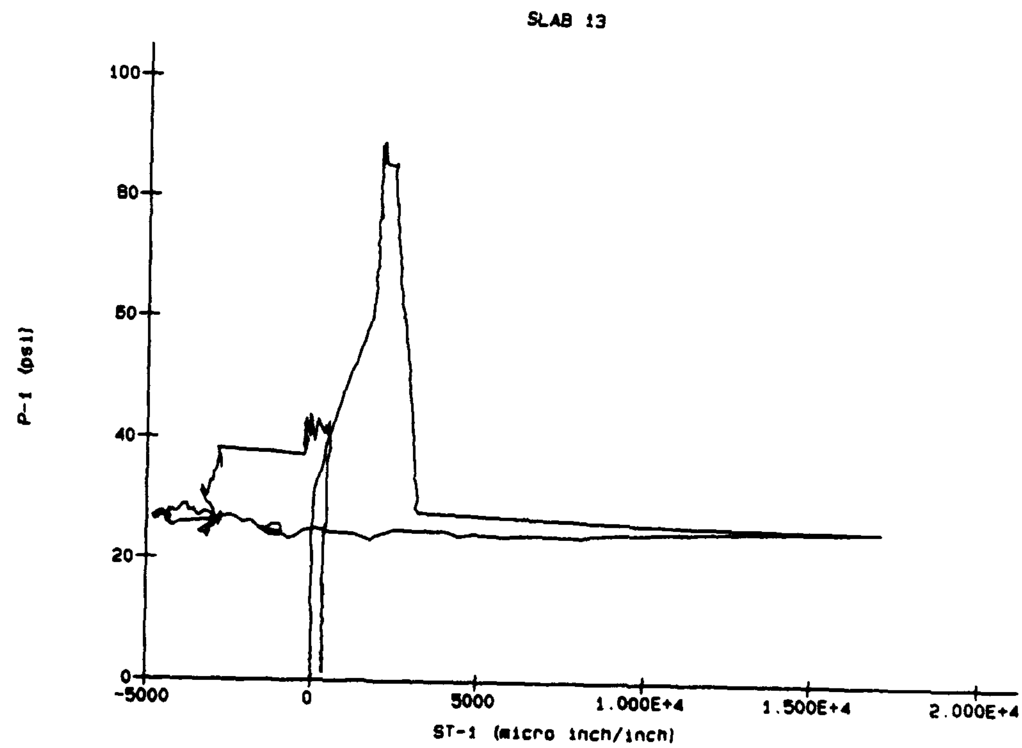
SLAB 13

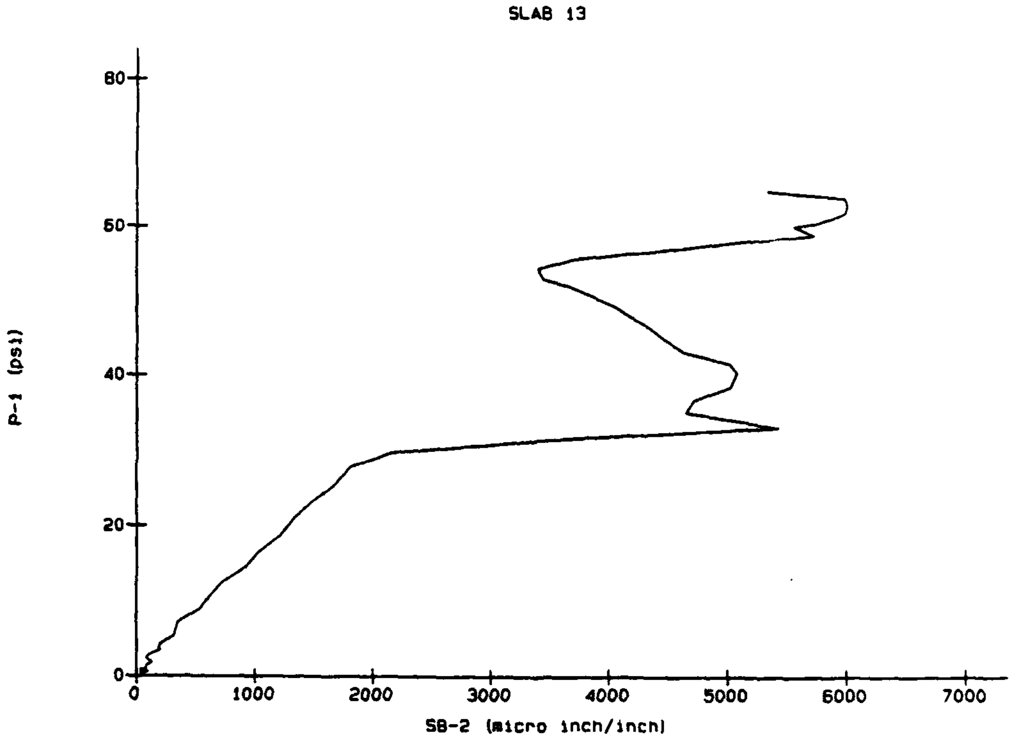


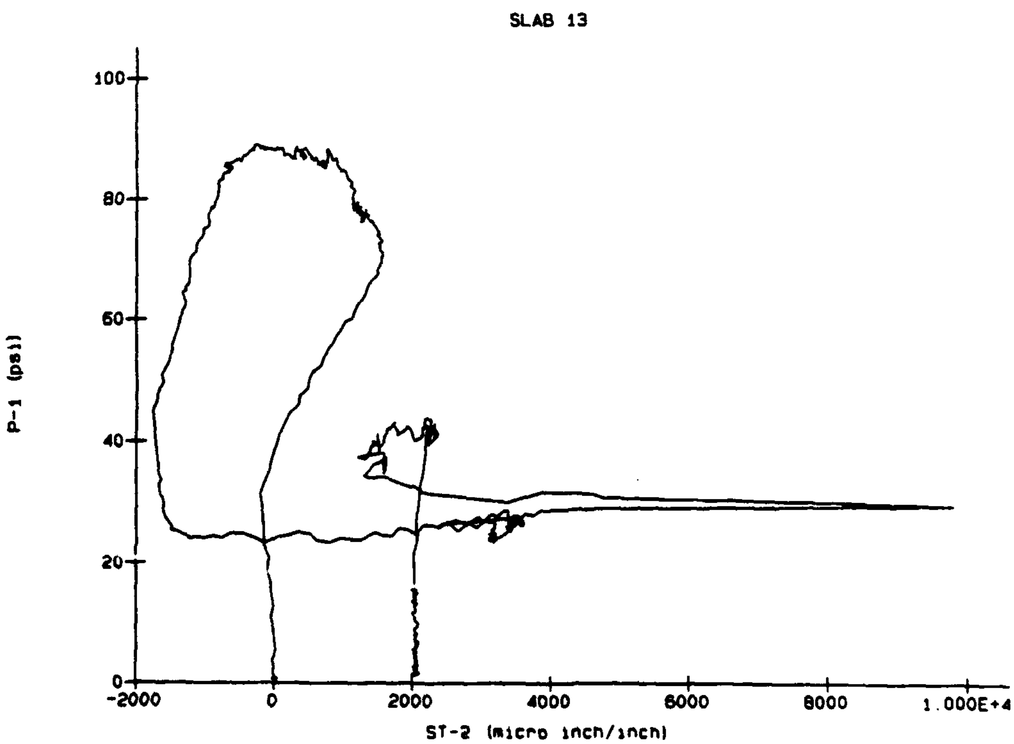
SLAB 13

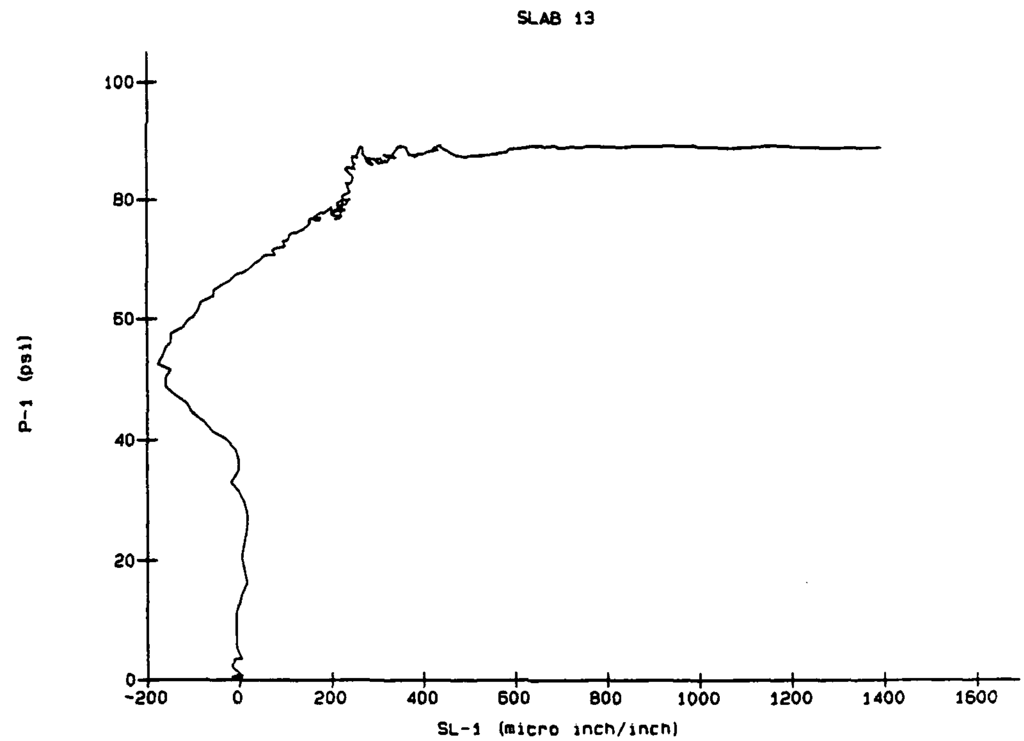


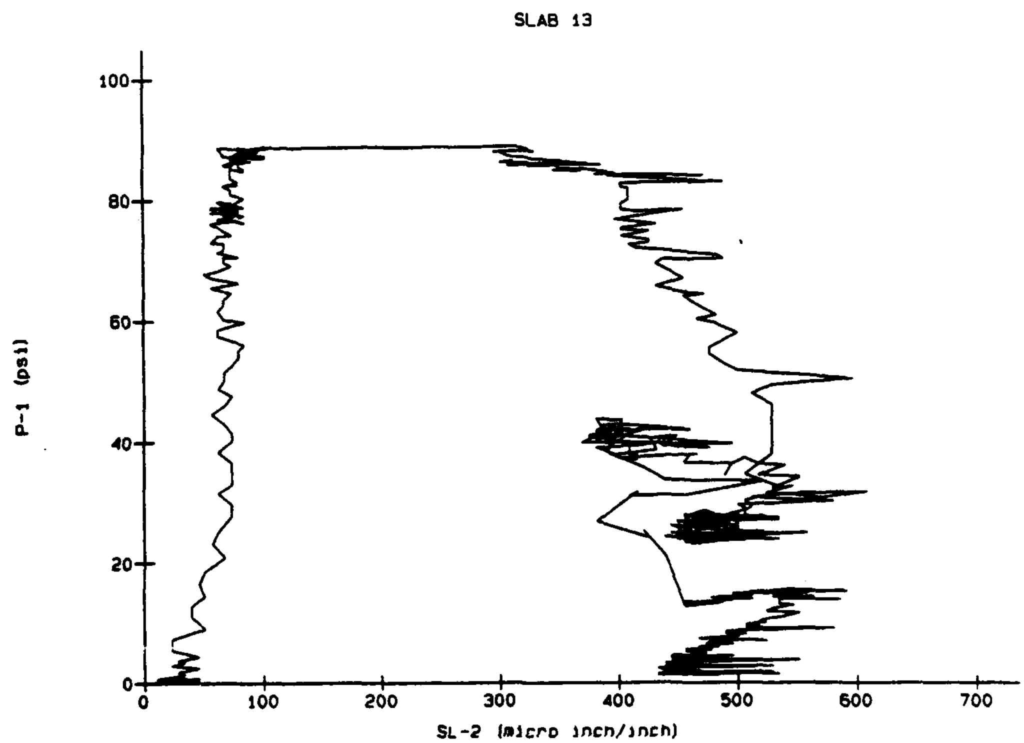

SLAB 13
P-1 (psi)
SB-1 (micro inch/inch)
0
20
40
60
80
100
0
200
400
600
800
1000
1200
1400
1600
1800


SLAB 13
P-1 (psi)
ST-1 (micro inch/inch)
0
20
40
60
80
100
-5000
0
5000
1.000E+4
1.500E+4
2.000E+4

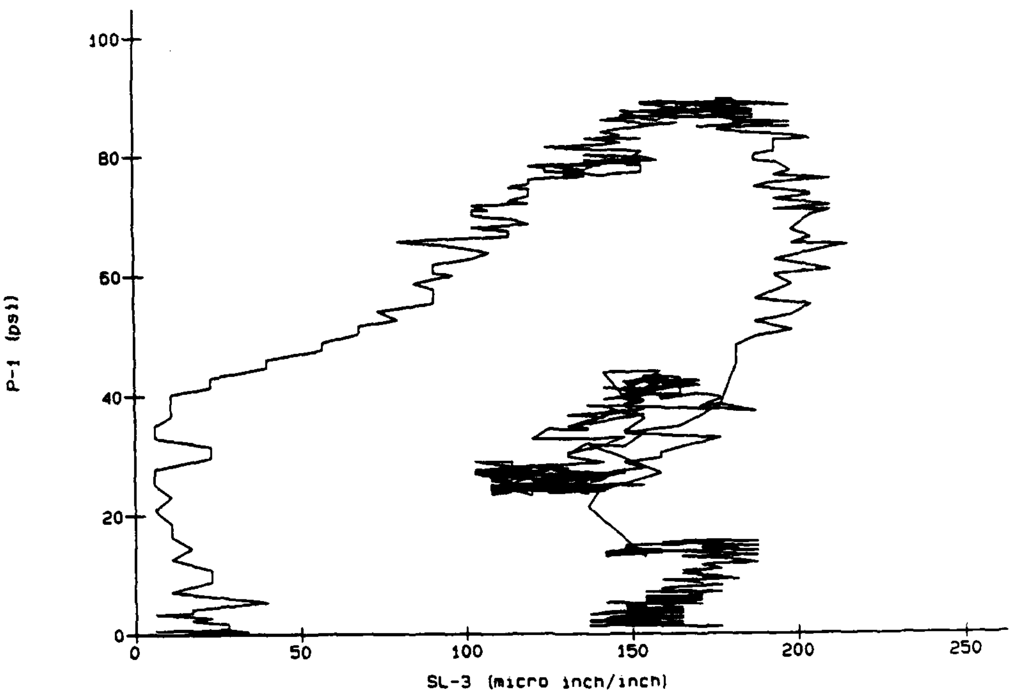

SLAB 13
P-1 (psi)
0
20
40
60
80
0
1000
2000
3000
4000
5000
6000
7000
SB-2 (micro inch/inch)


SLAB 13
P-1 (psi)
0
20
40
60
80
100
-2000
0
2000
4000
6000
8000
1.000E+4
ST-2 (micro inch/inch)

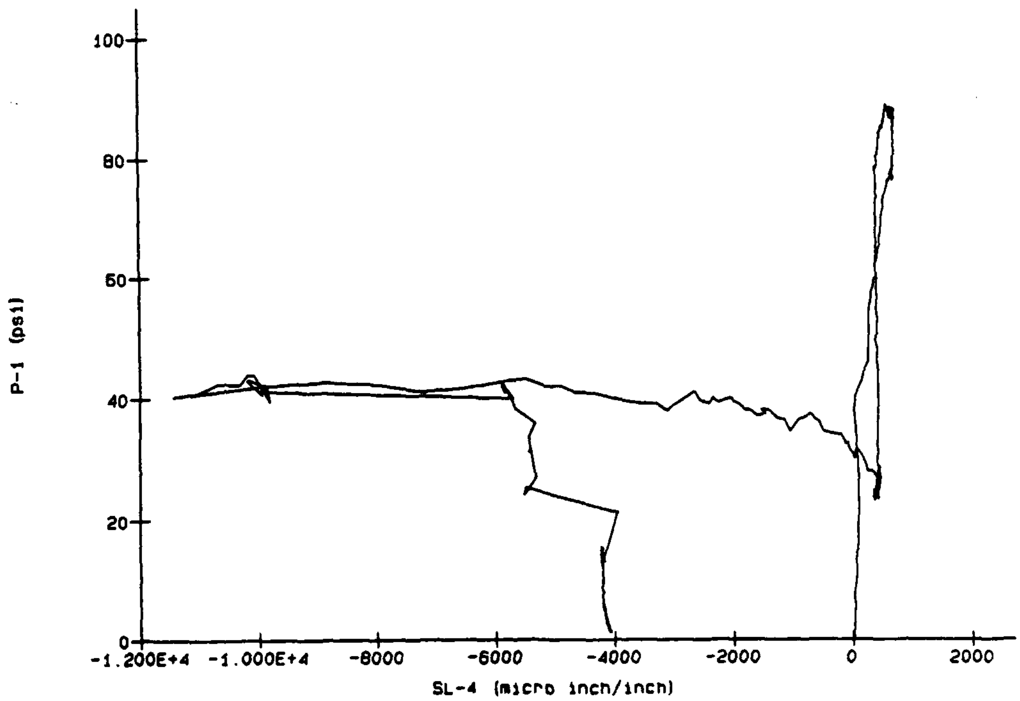

SLAB 13
100
80
60
40
20
0
-200
0
200
400
600
800
1000
1200
1400
1600
SL-1 (micro inch/inch)
P-1 (psi)

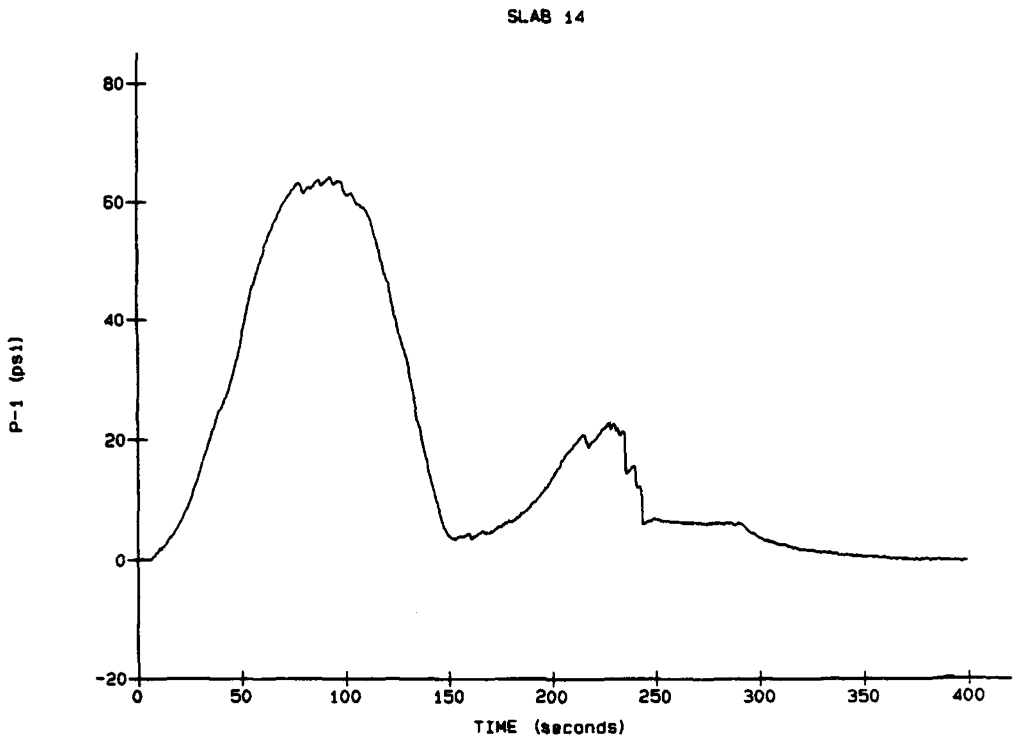

SLAB 13
100
80
60
40
20
0
0
100
200
300
400
500
600
700
SL-2 (micro inch/inch)
P-1 (psi)

SLAB 13

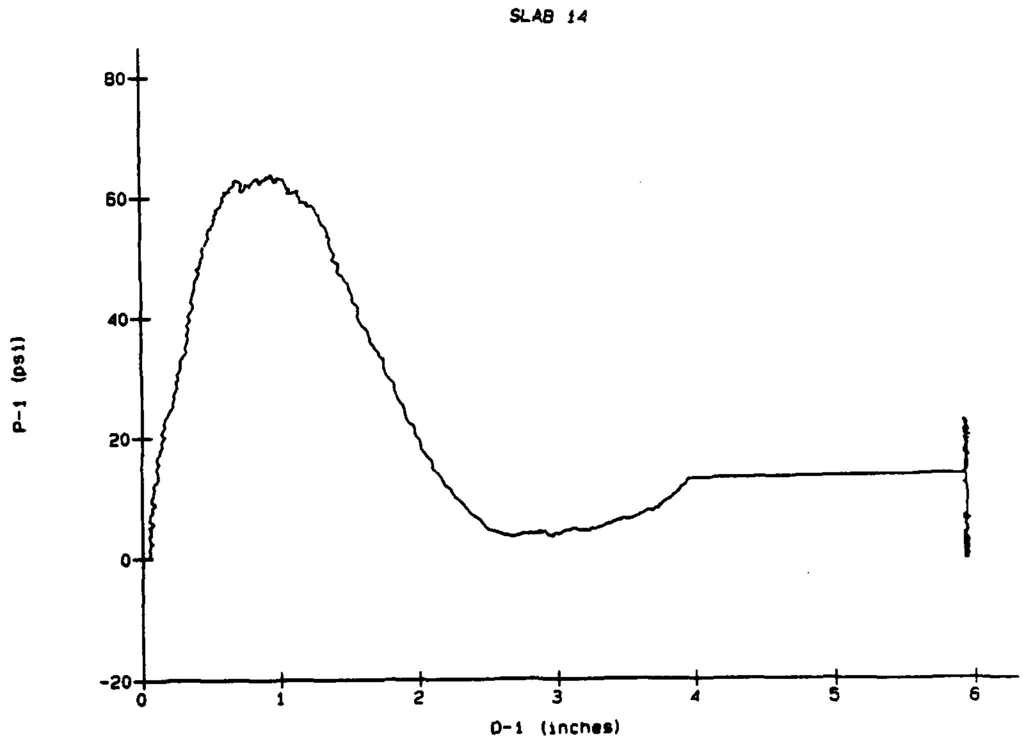


SLAB 13

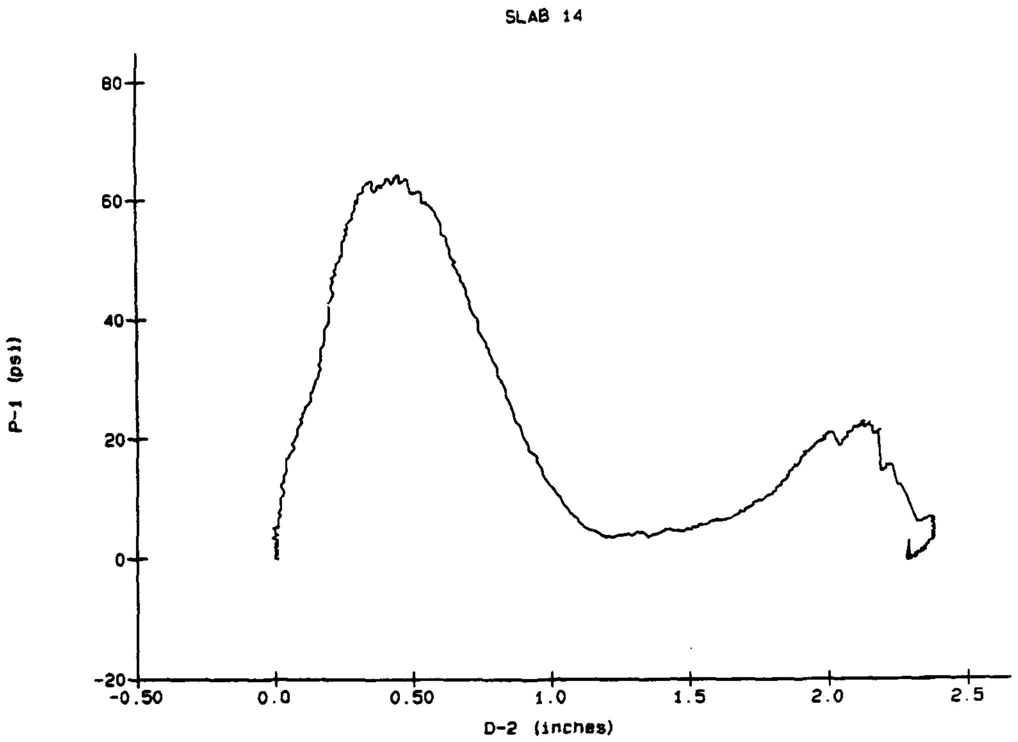




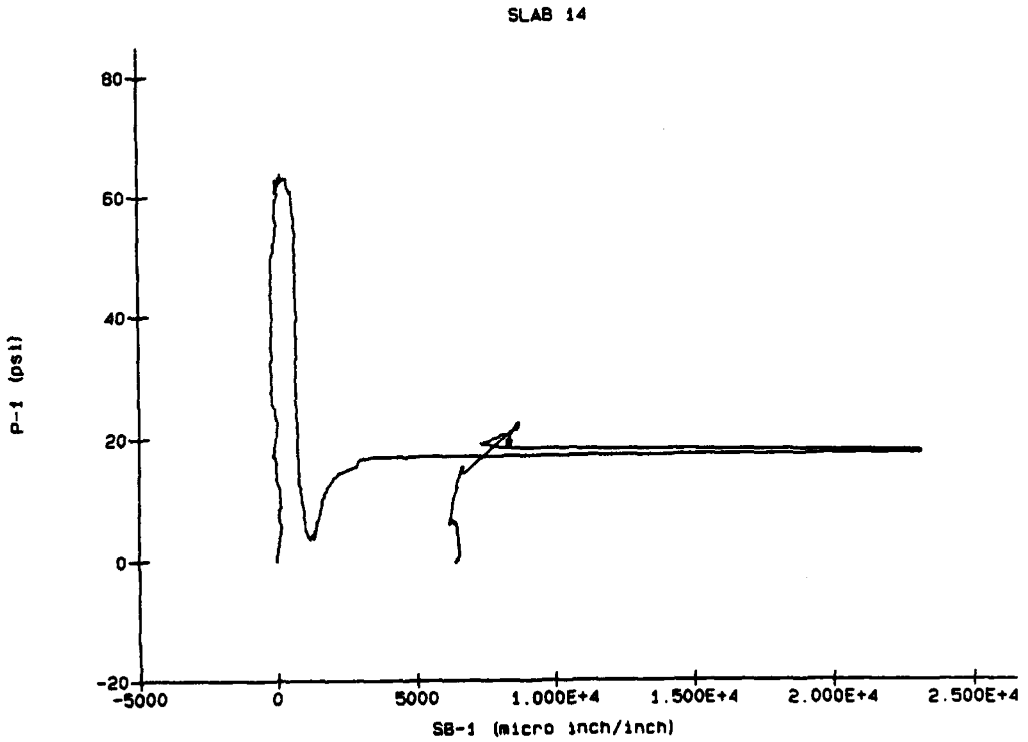
SLAB 14
80
60
40
20
0
-20
P-1 (psi)
0
50
100
150
200
250
300
350
400
TIME (seconds)



SLAB 14
80
60
40
20
0
-20
P-1 (psi)
0
1
2
3
4
5
6
D-1 (inches)

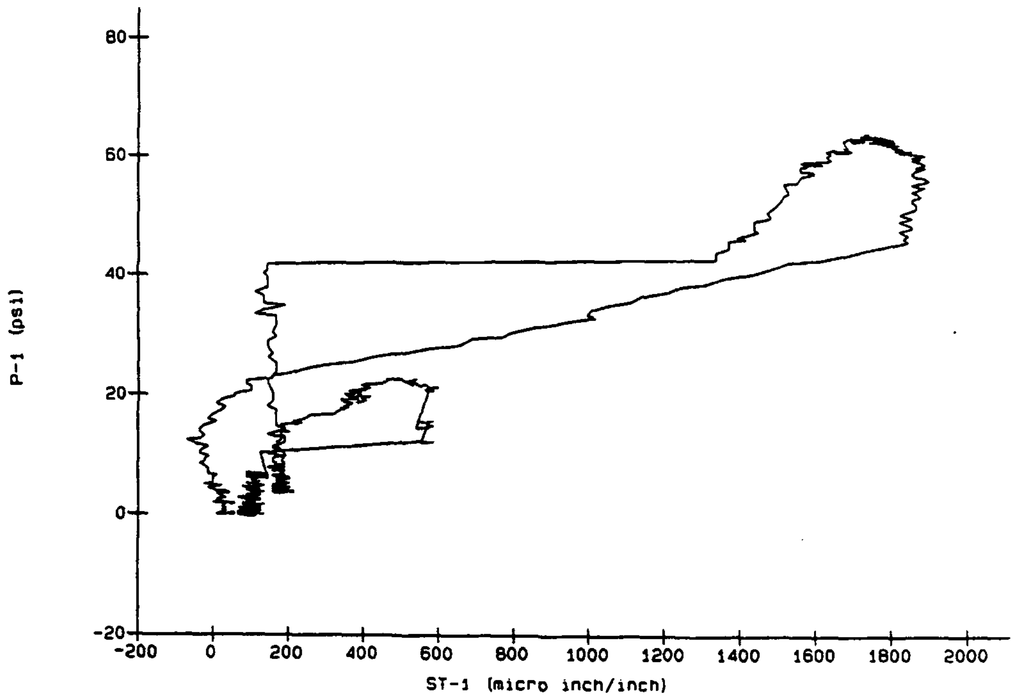


SLAB 14
80
60
40
20
0
-20
P-1 (psi)
-0.50
0.0
0.50
1.0
1.5
2.0
2.5
D-2 (inches)

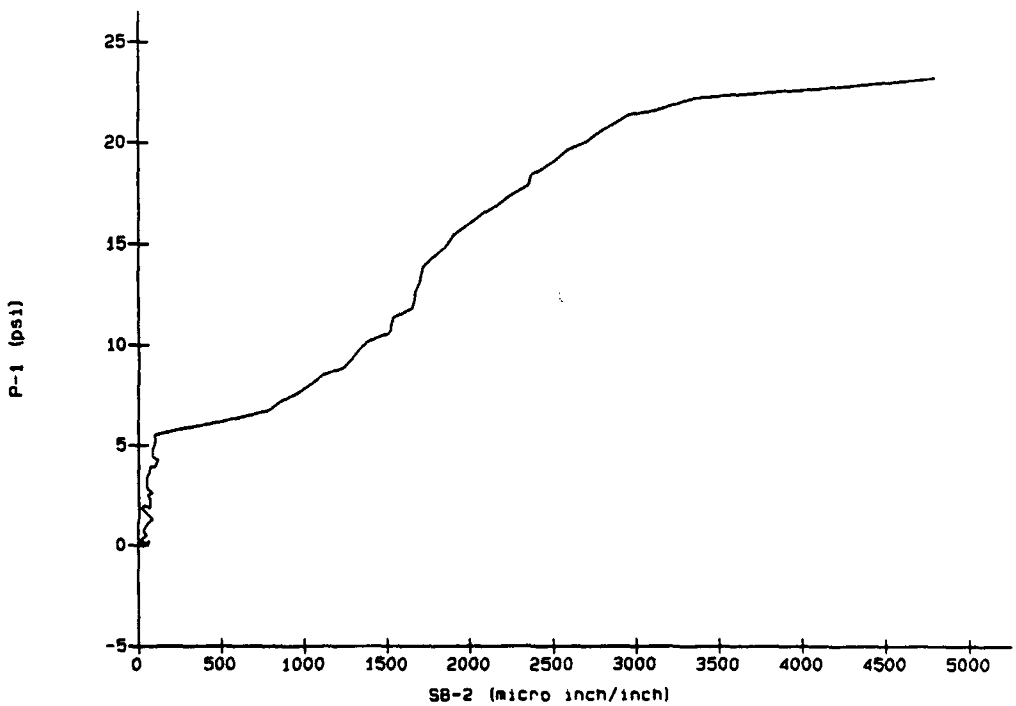


SLAB 14
80
60
40
20
0
-20
P-1 (psi)
-5000
0
5000
1.000E+4
1.500E+4
2.000E+4
2.500E+4
SB-1 (micro inch/inch)

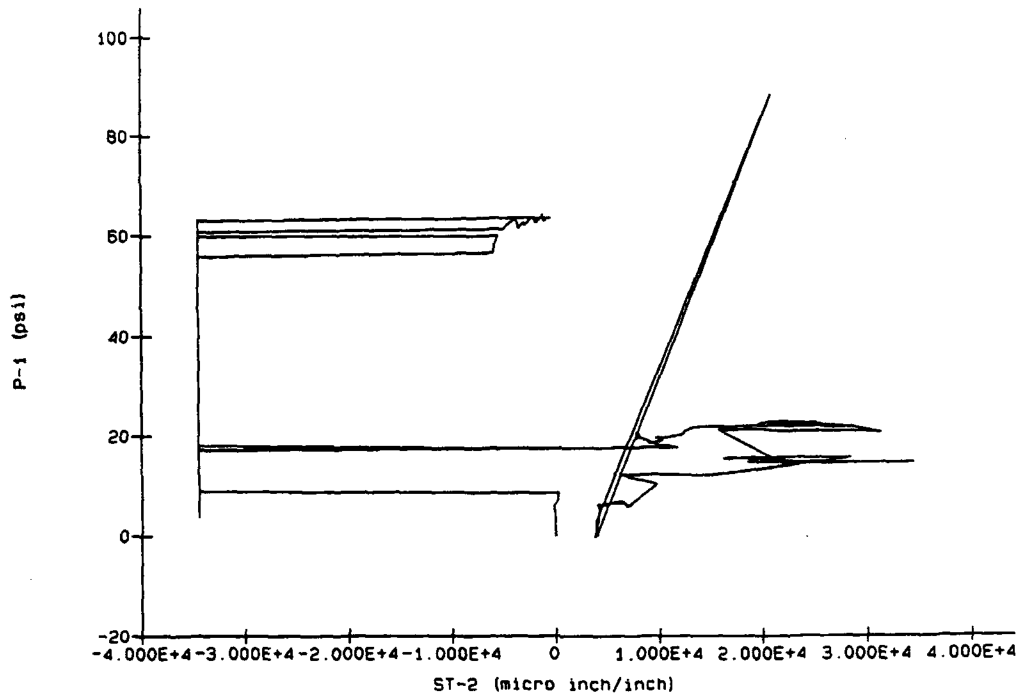
SLAB 14



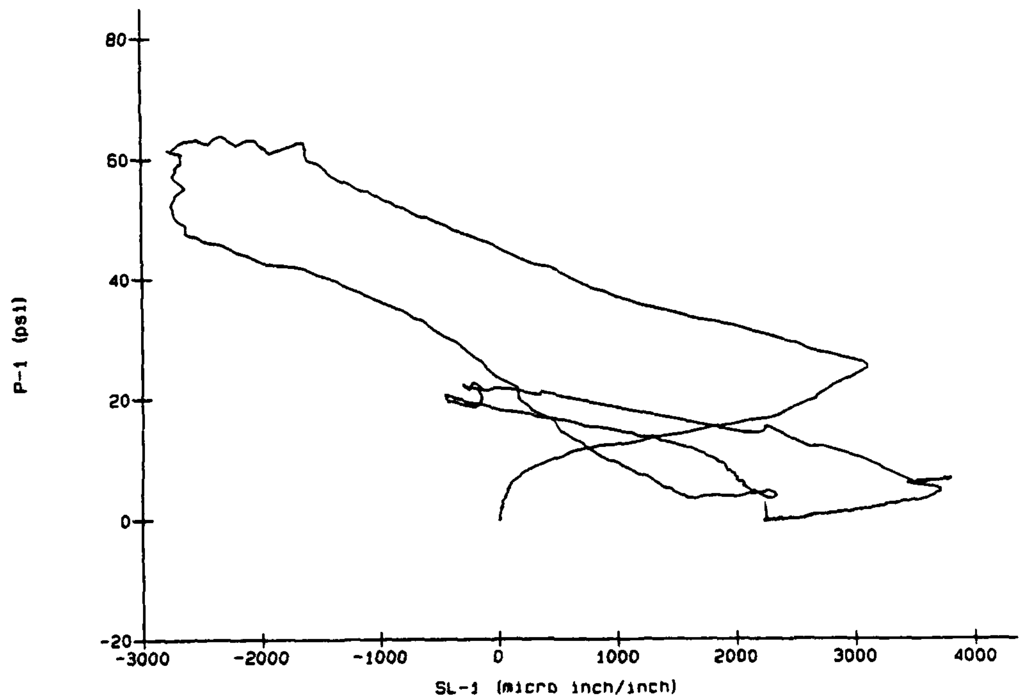
SLAB 14



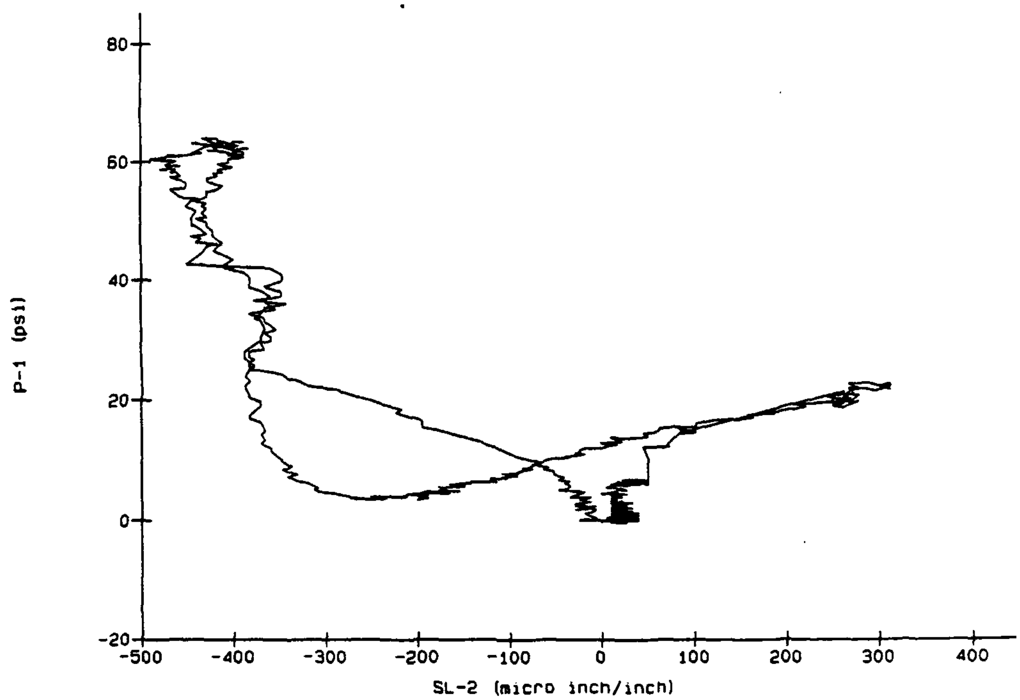
SLAB 14



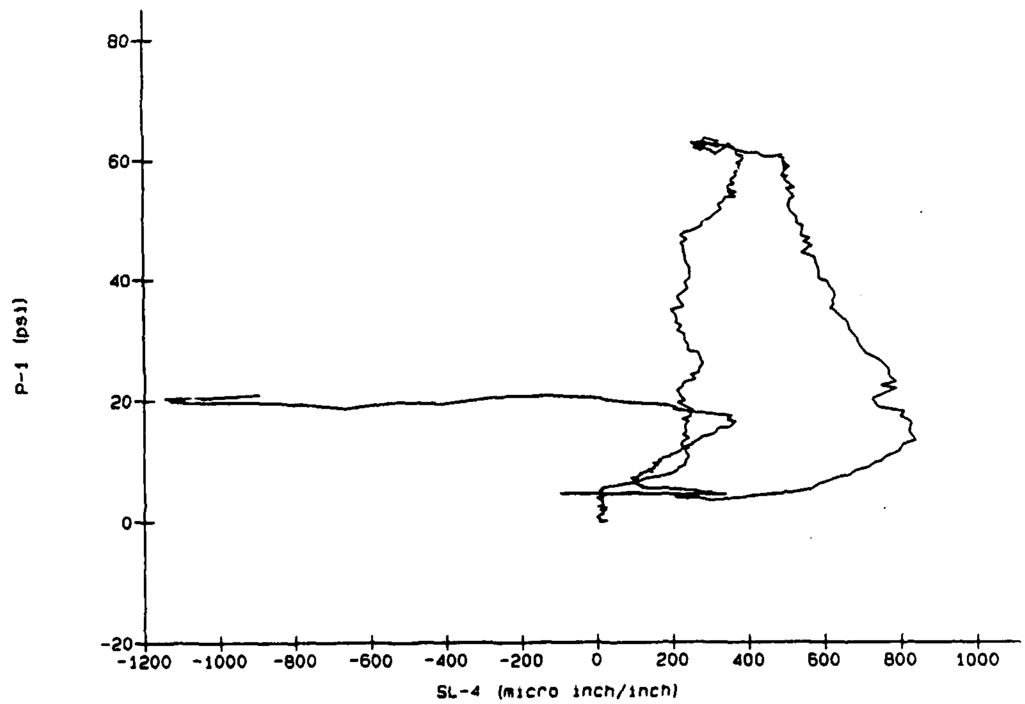
SLAB 14



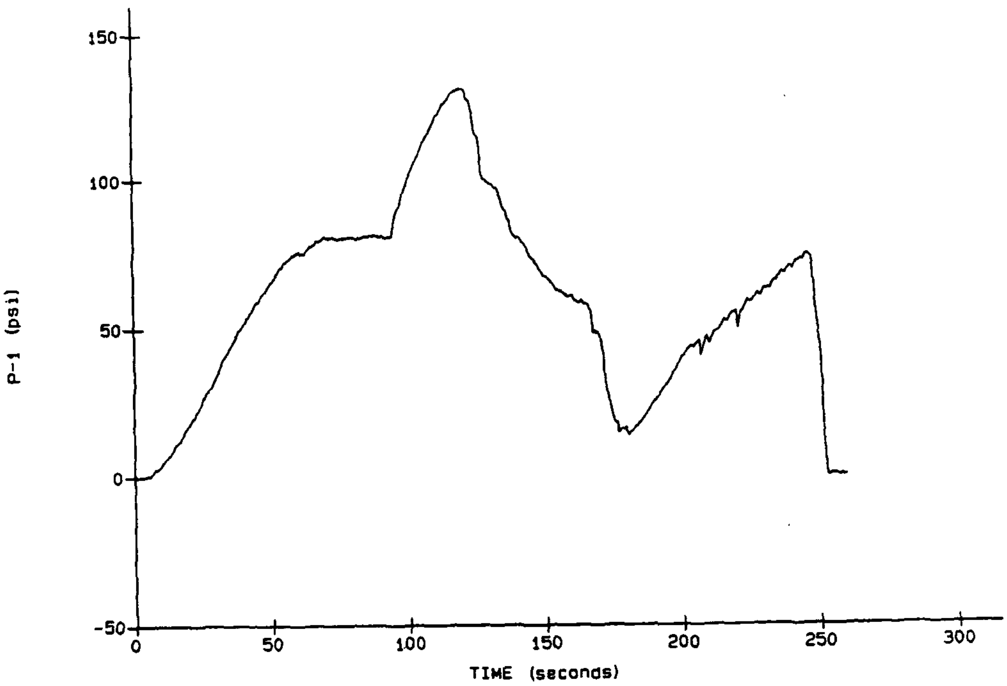
SLAB 14



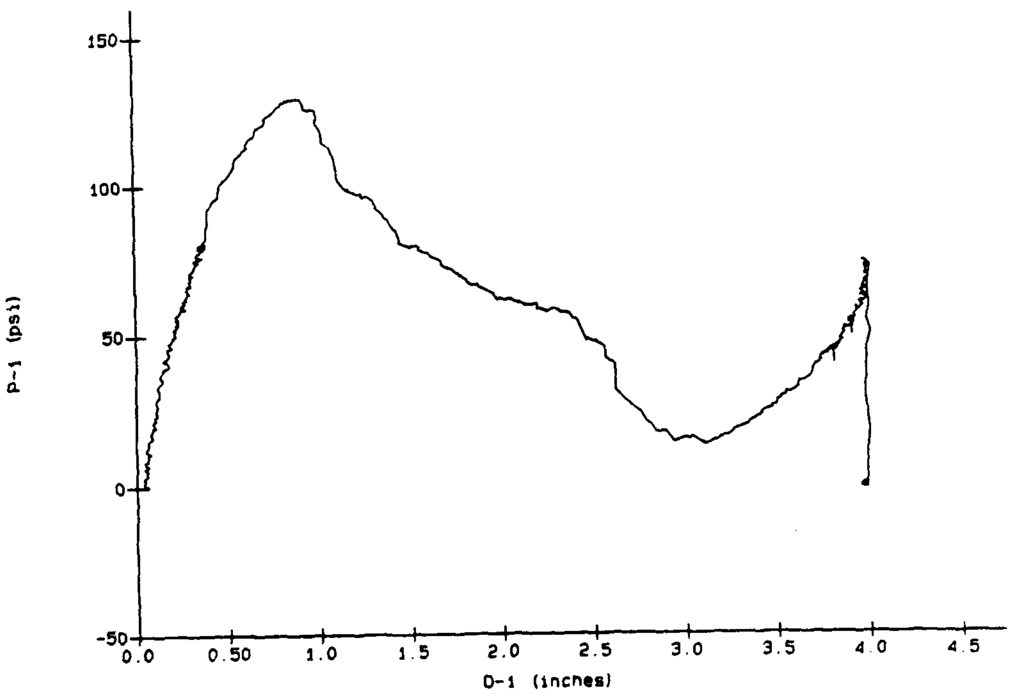
SLAB 14

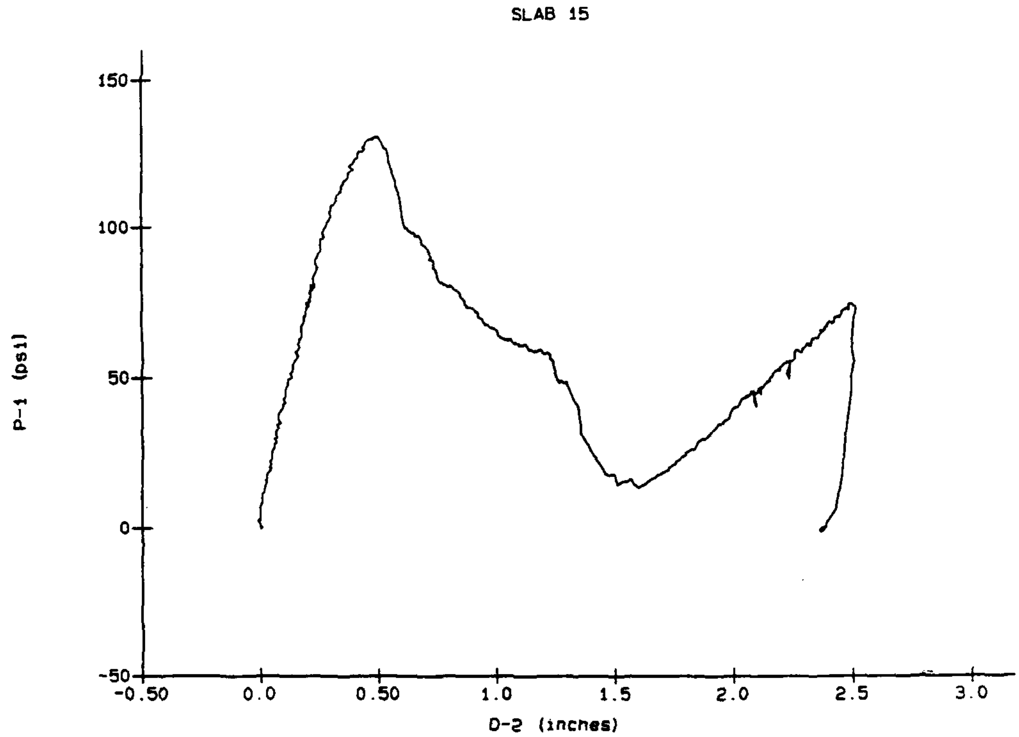


SLAB 15

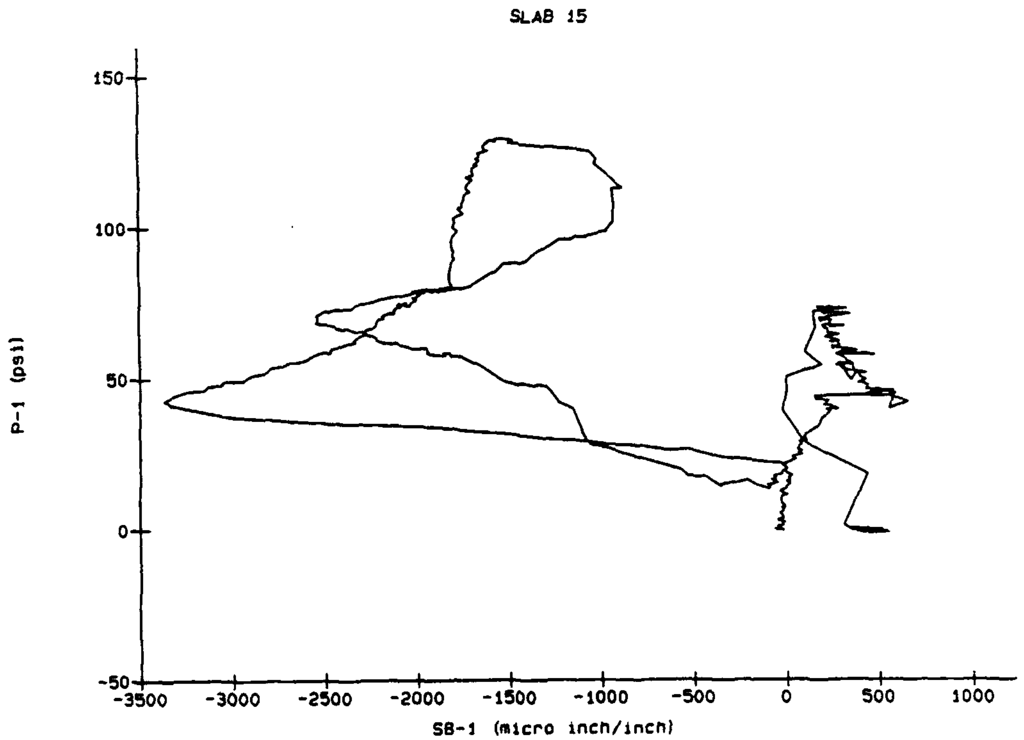


SLAB 15

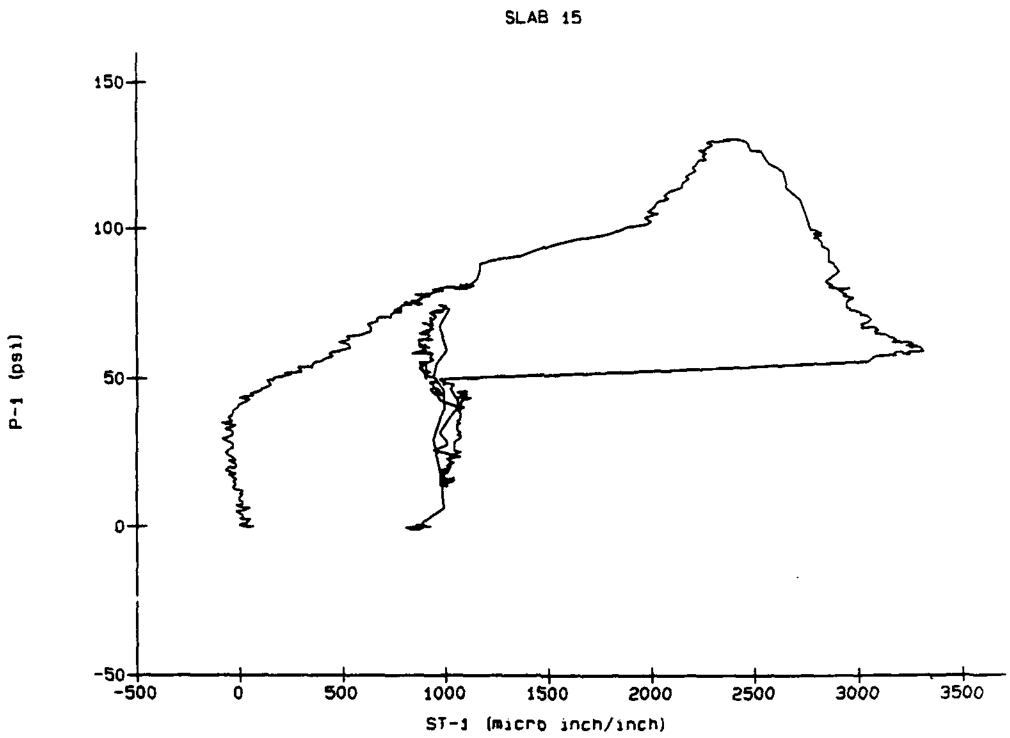


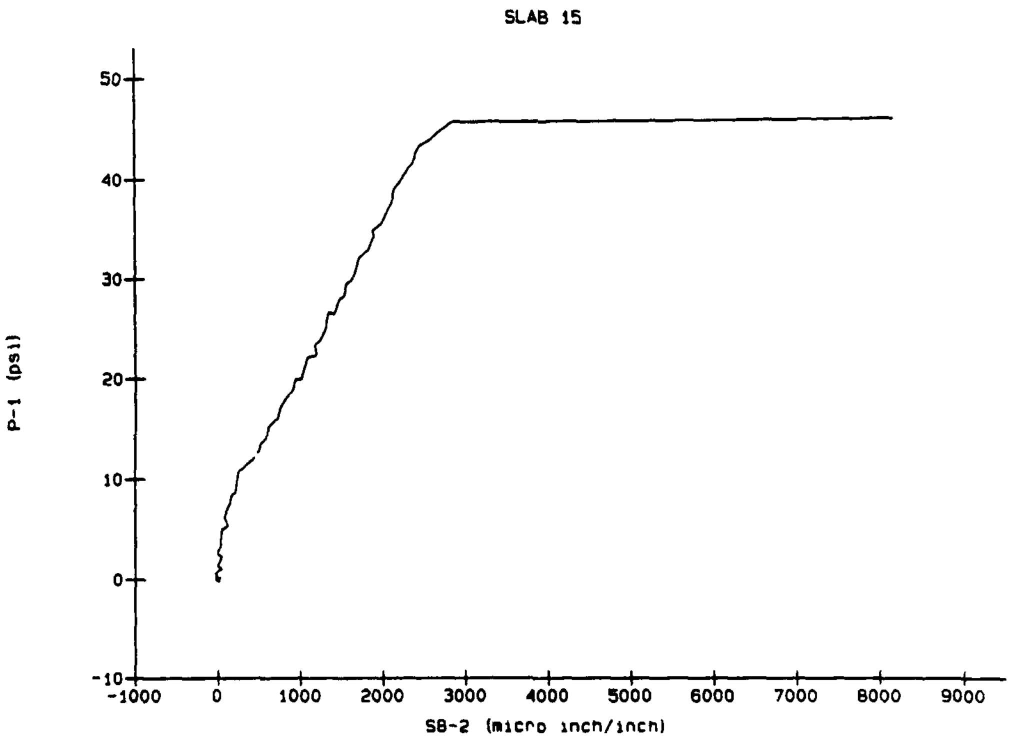


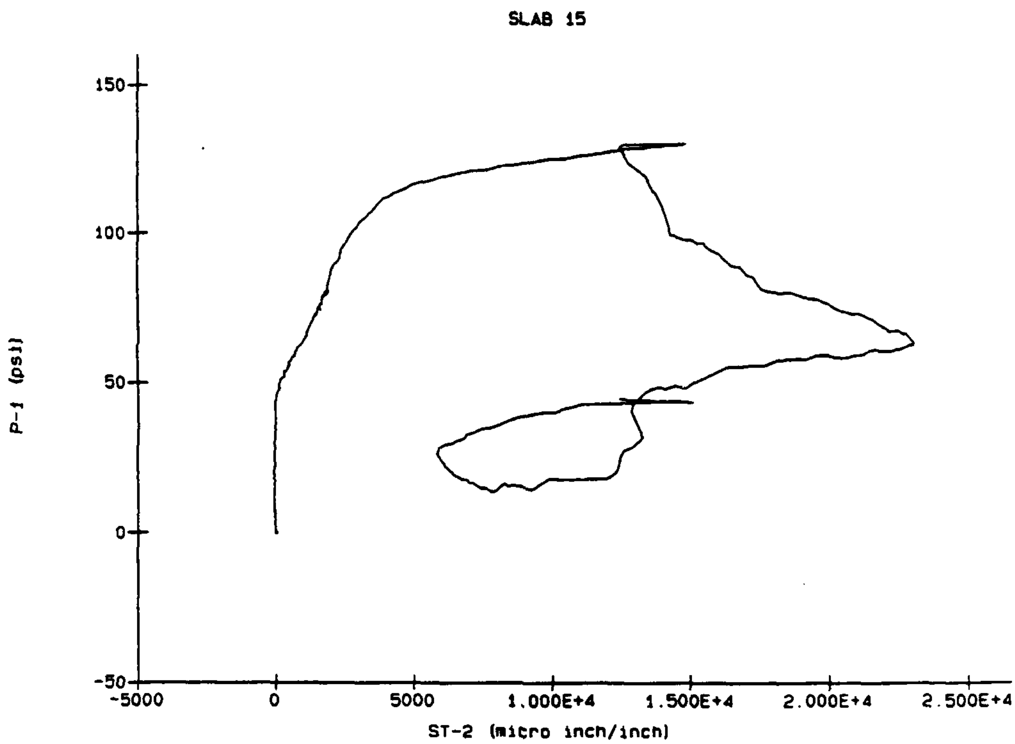
SLAB 15
P-1 (psi)
150
100
50
0
-50
-0.50
0.0
0.50
1.0
1.5
2.0
2.5
3.0
D-2 (inches)

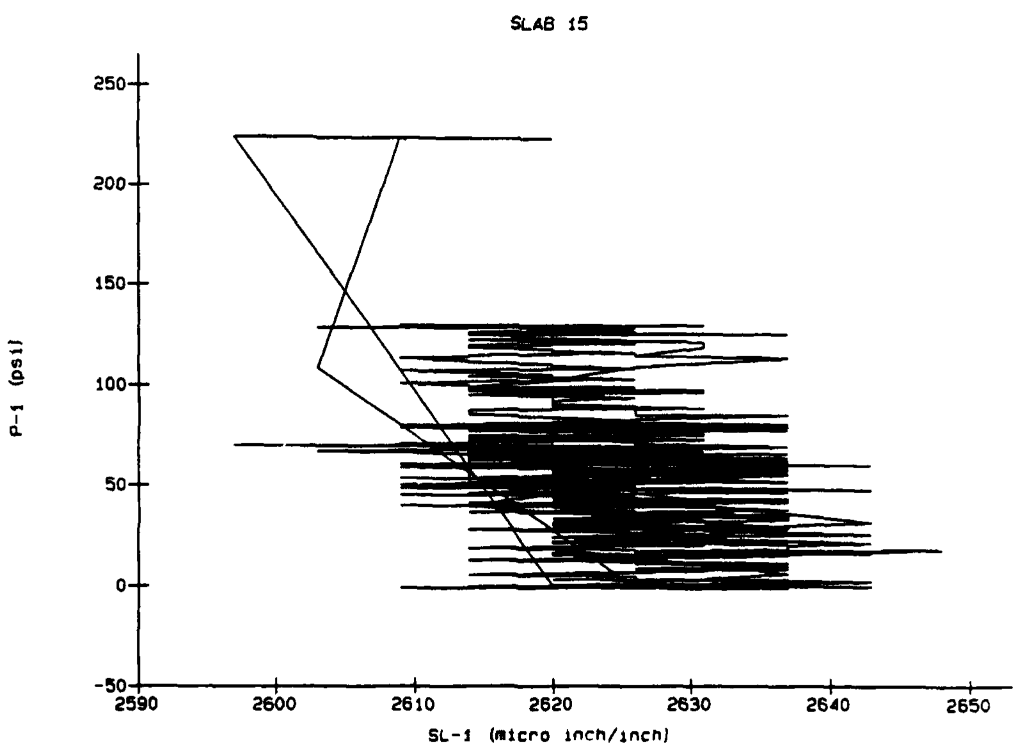


SLAB 15
P-1 (psi)
150
100
50
0
-50
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
SB-1 (micro inch/inch)

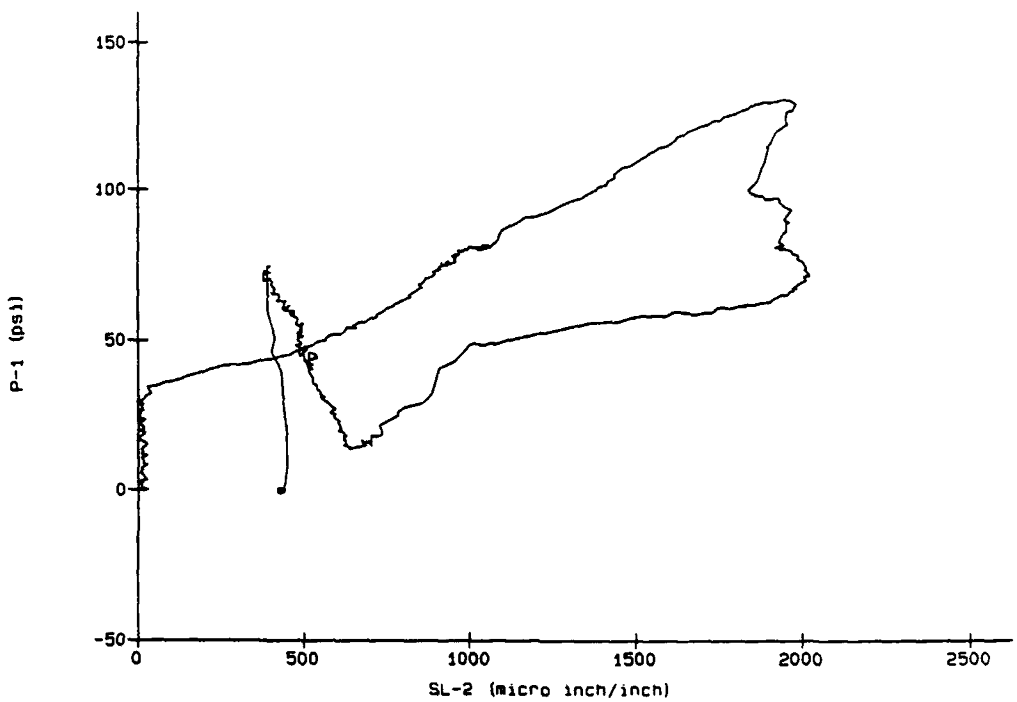

SLAB 15
P-1 (psi)
150
100
50
0
-50
-500
0
500
1000
1500
2000
2500
3000
3500
ST-1 (micro inch/inch)


SLAB 15
P-1 (psi)
50
40
30
20
10
0
-10
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
SB-2 (micro inch/inch)

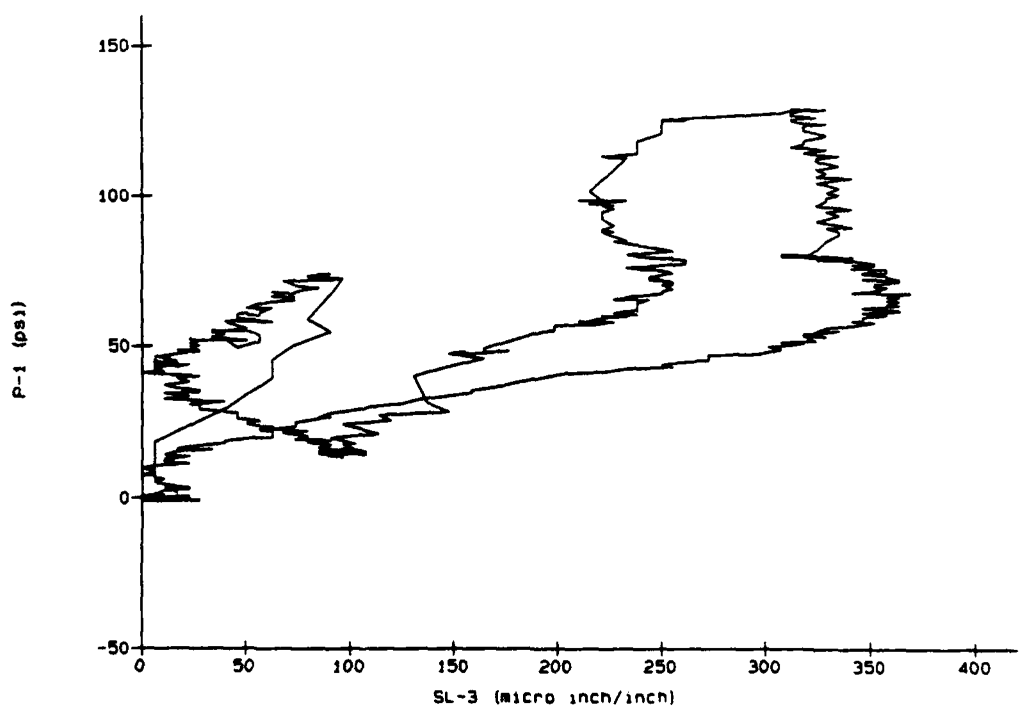

SLAB 15
150
100
50
0
-50
P-1 (psi)
-5000
0
5000
1.000E+4
1.500E+4
2.000E+4
2.500E+4
ST-2 (micro inch/inch)


SLAB 15
250
200
150
100
50
0
-50
P-1 (psi)
2590
2600
2610
2620
2630
2640
2650
SL-1 (micro inch/inch)

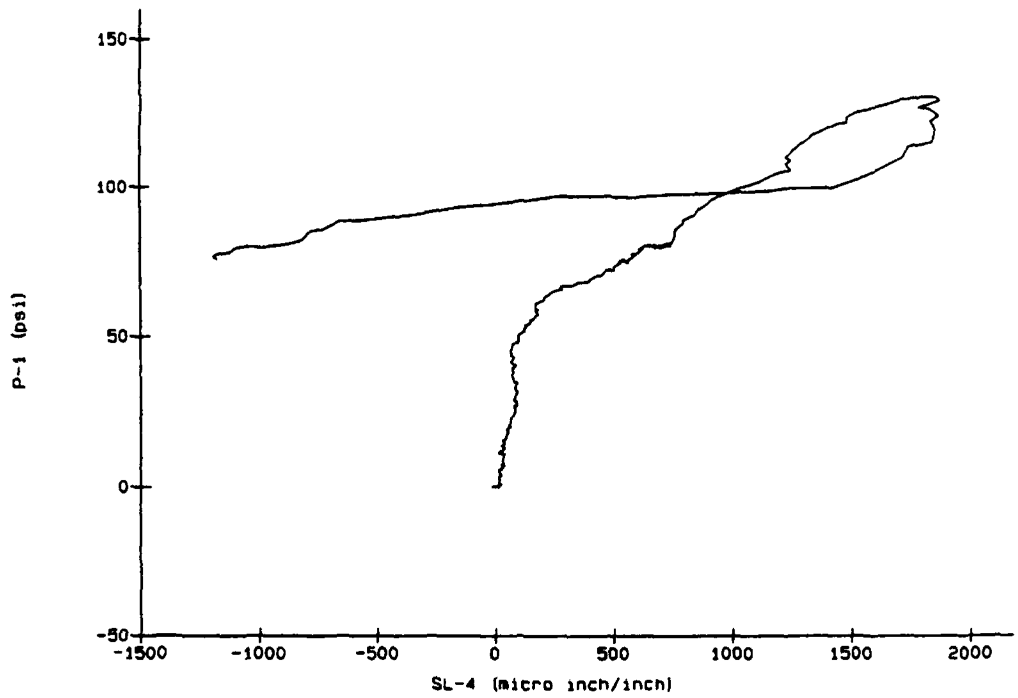
SLAB 15



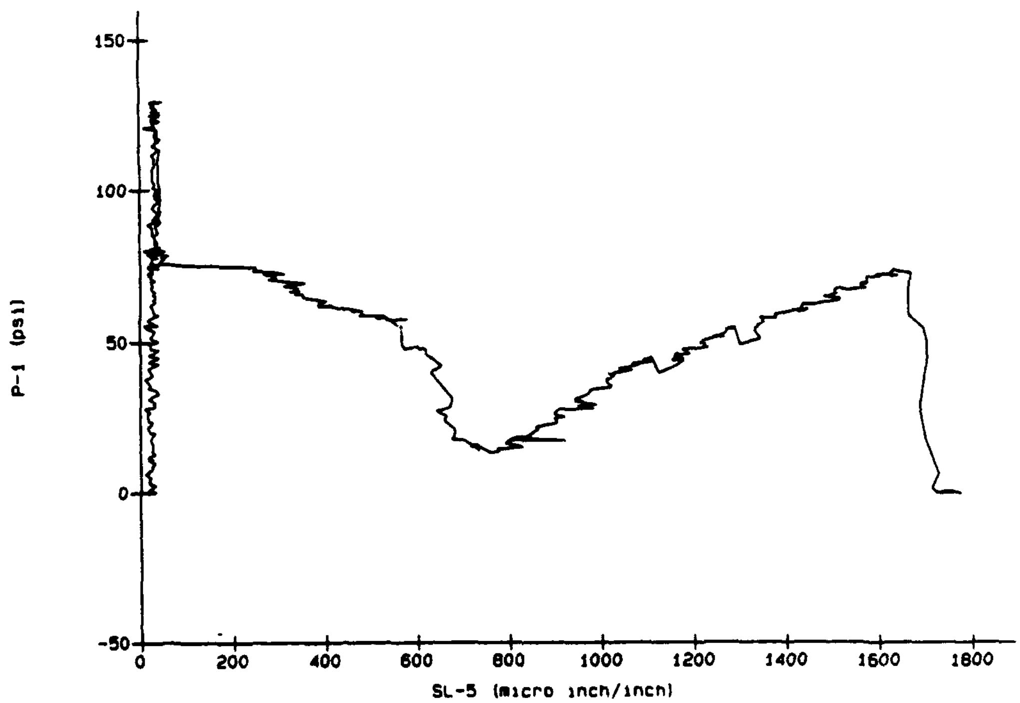
SLAB 15



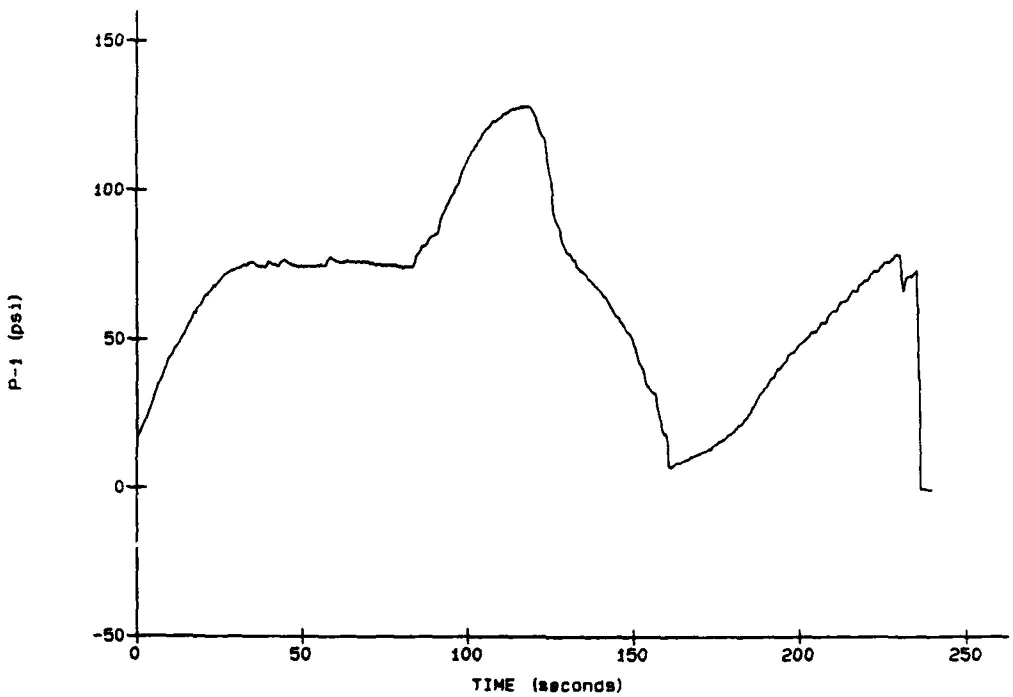
SLAB 15



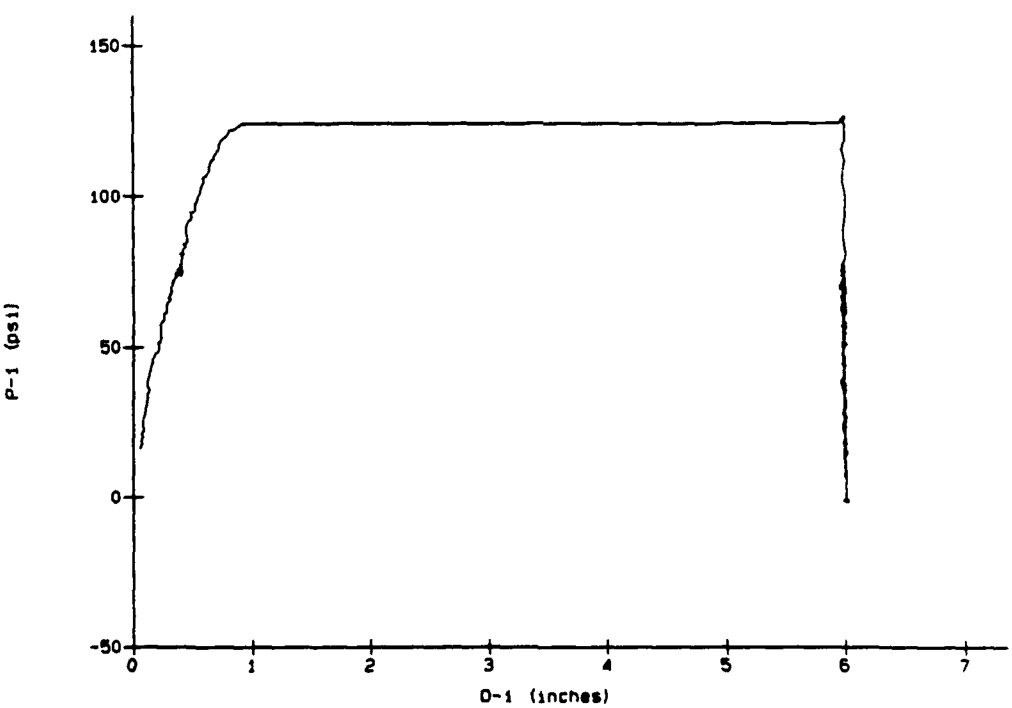
SLAB 15

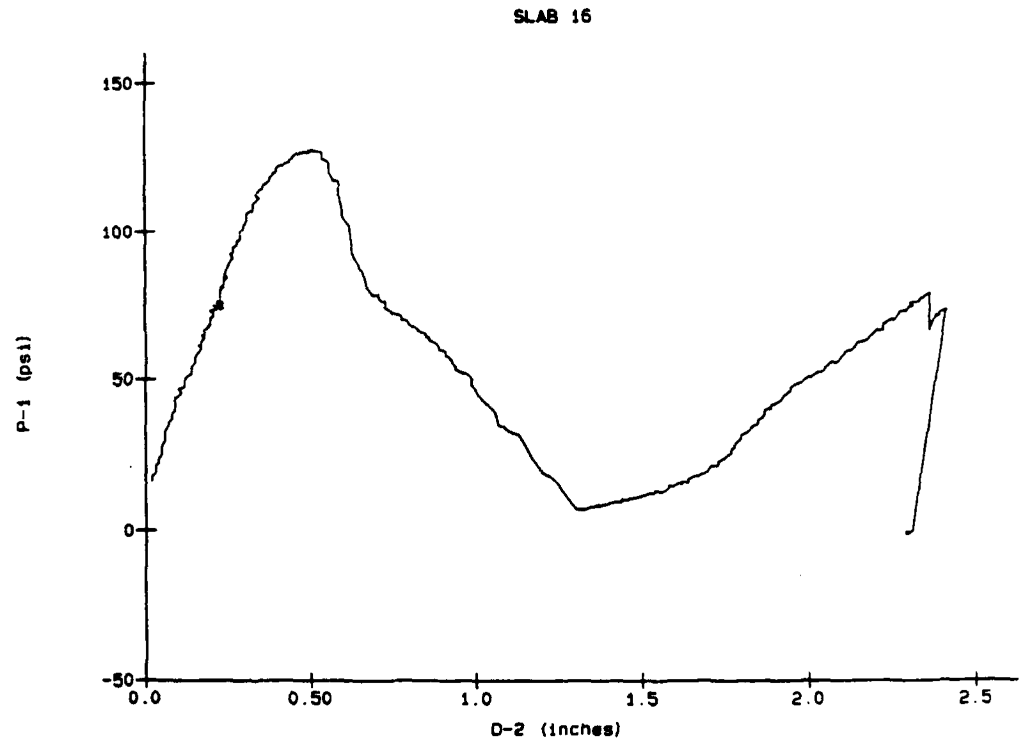


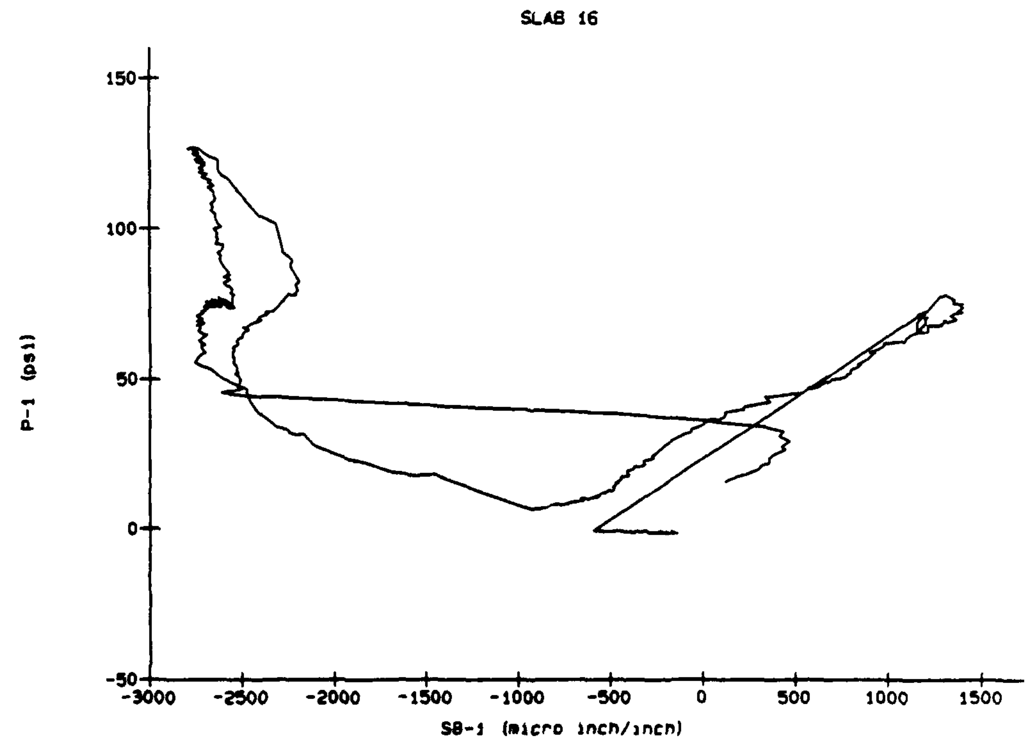
SLAB 16

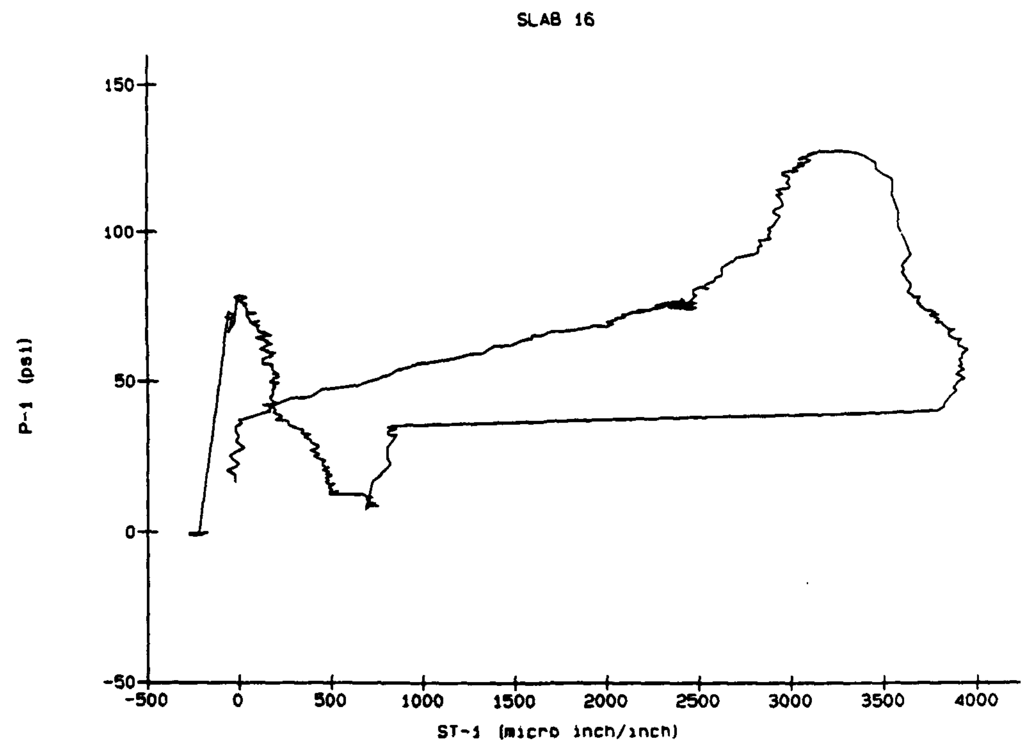


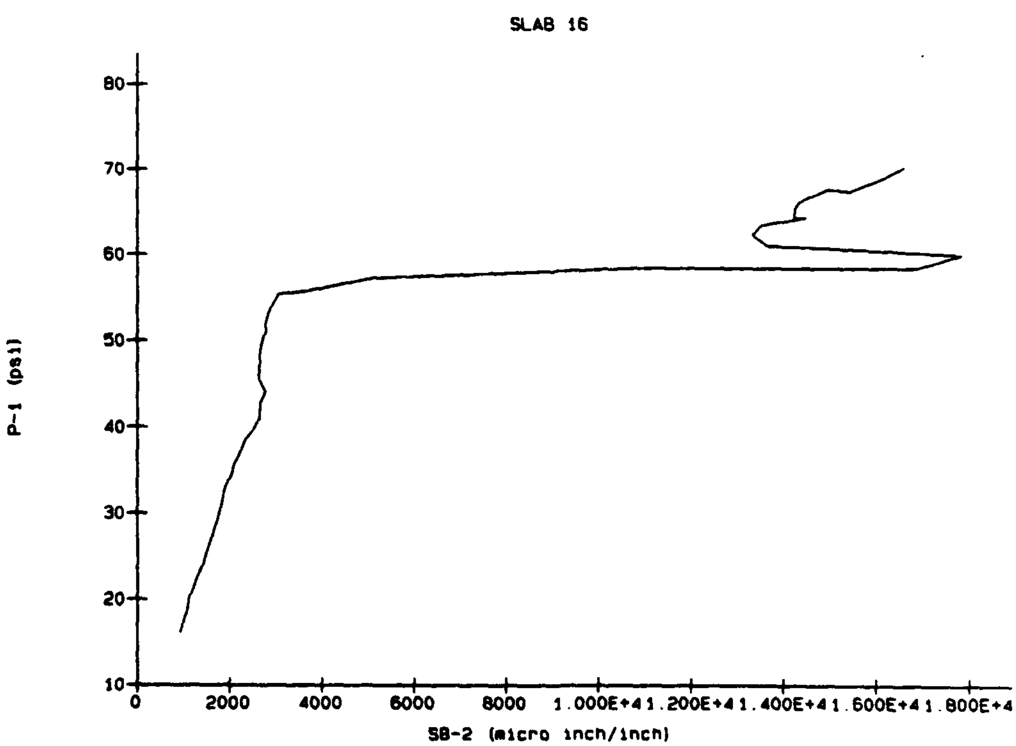
SLAB 16



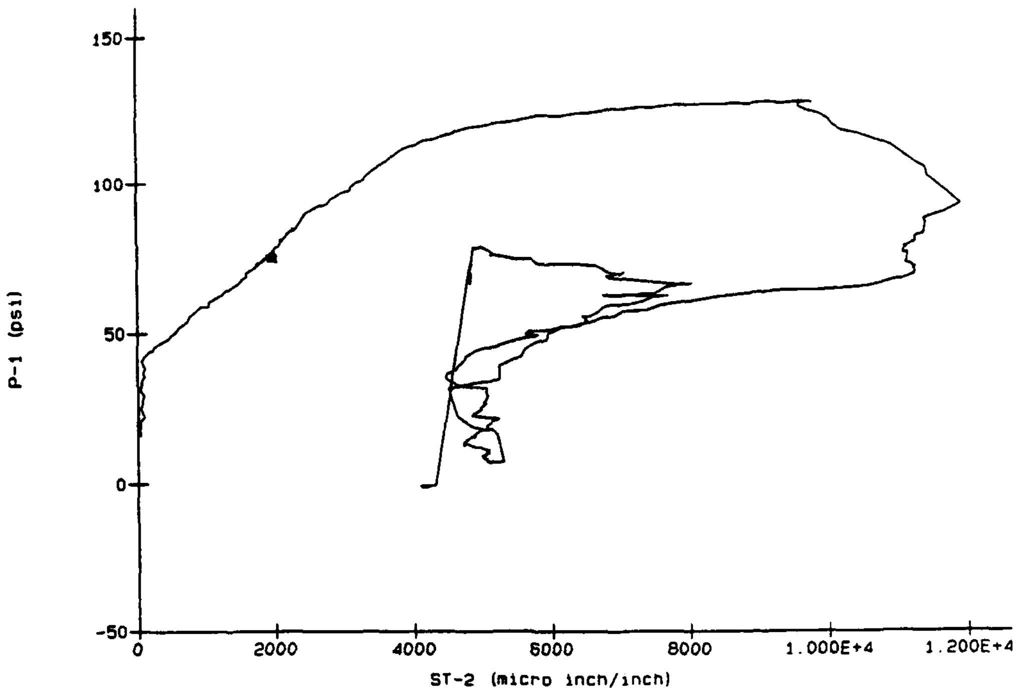

SLAB 16
150
100
50
0
-50
P-1 (psi)
0.0
0.50
1.0
1.5
2.0
2.5
D-2 (inches)


SLAB 16
150
100
50
0
-50
P-1 (psi)
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
SG-1 (micro inch/inch)

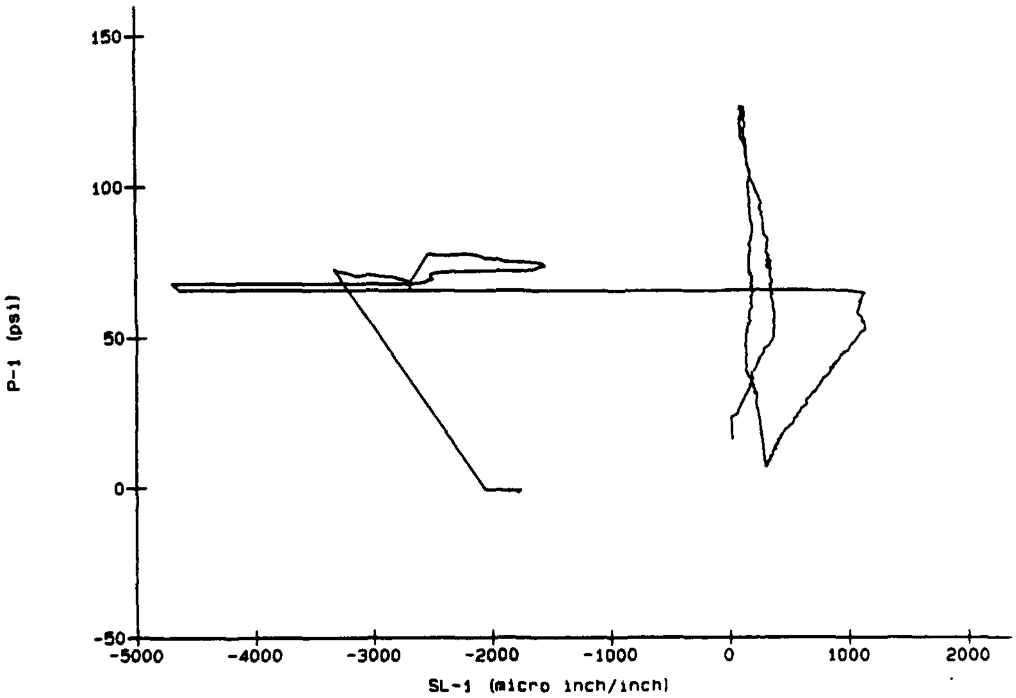

SLAB 16
P-1 (psi)
150
100
50
0
-50
-500
0
500
1000
1500
2000
2500
3000
3500
4000
ST-1 (micro inch/inch)

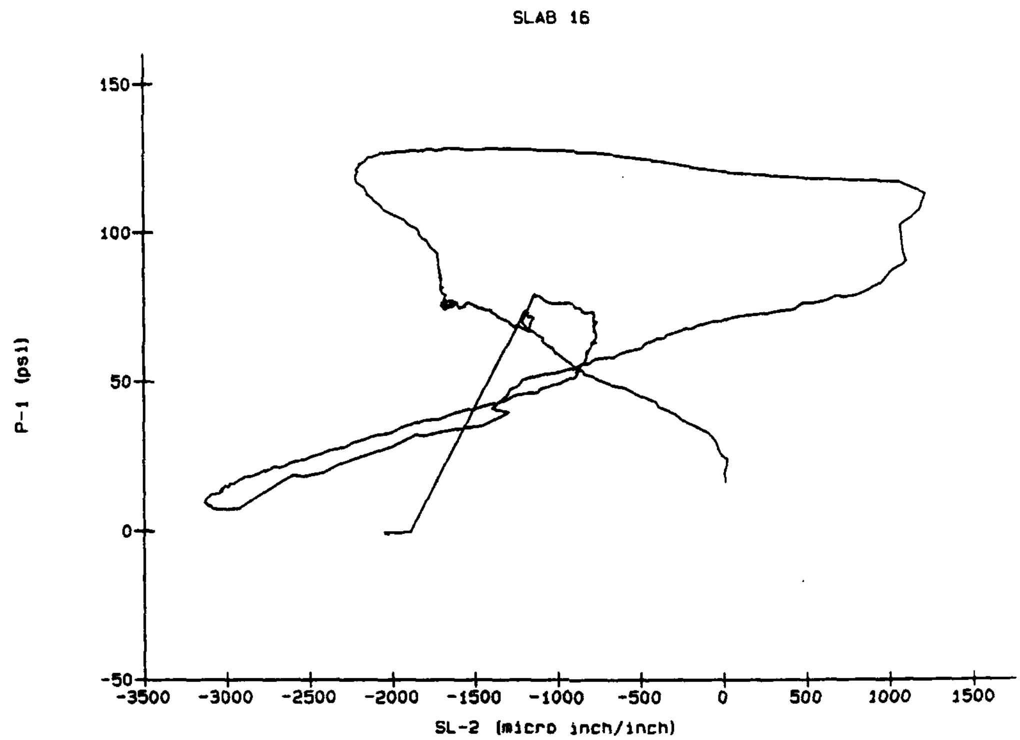

SLAB 16
P-1 (psi)
80
70
60
50
40
30
20
10
0
2000
4000
6000
8000
1.000E+4
1.200E+4
1.400E+4
1.600E+4
1.800E+4
SB-2 (micro inch/inch)

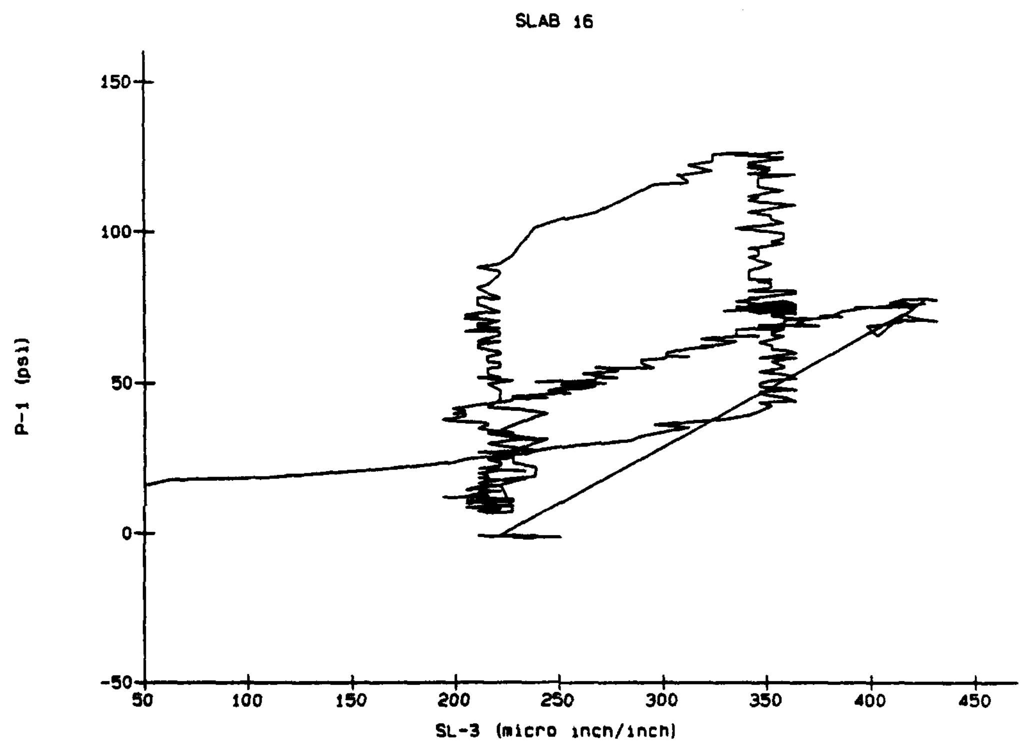
SLAB 16

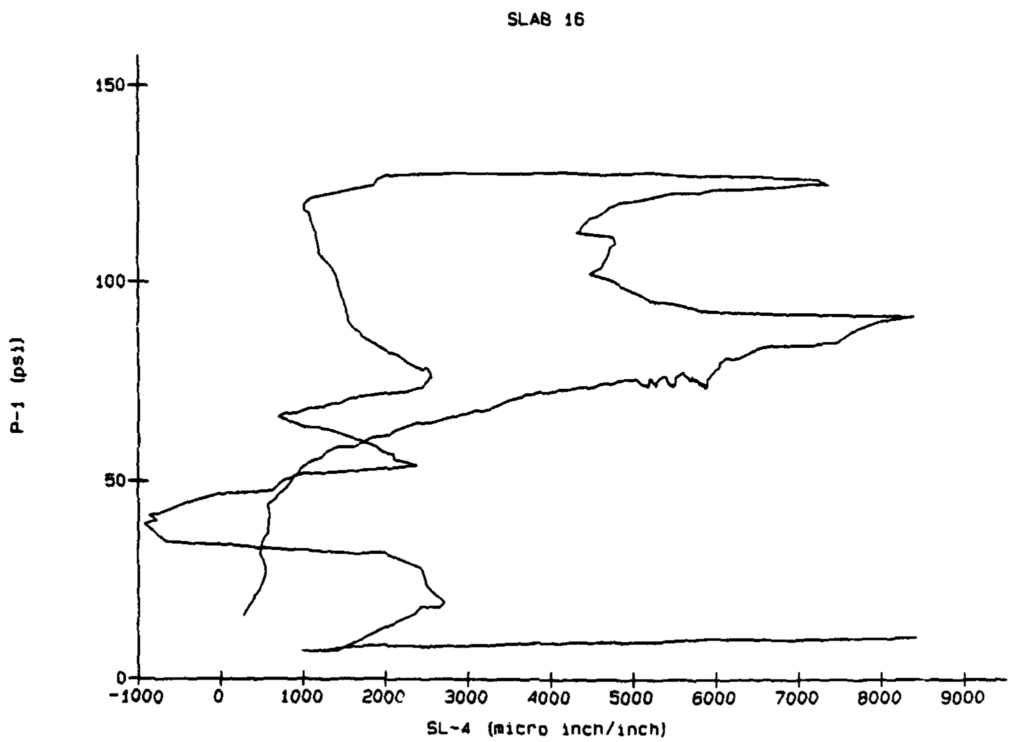


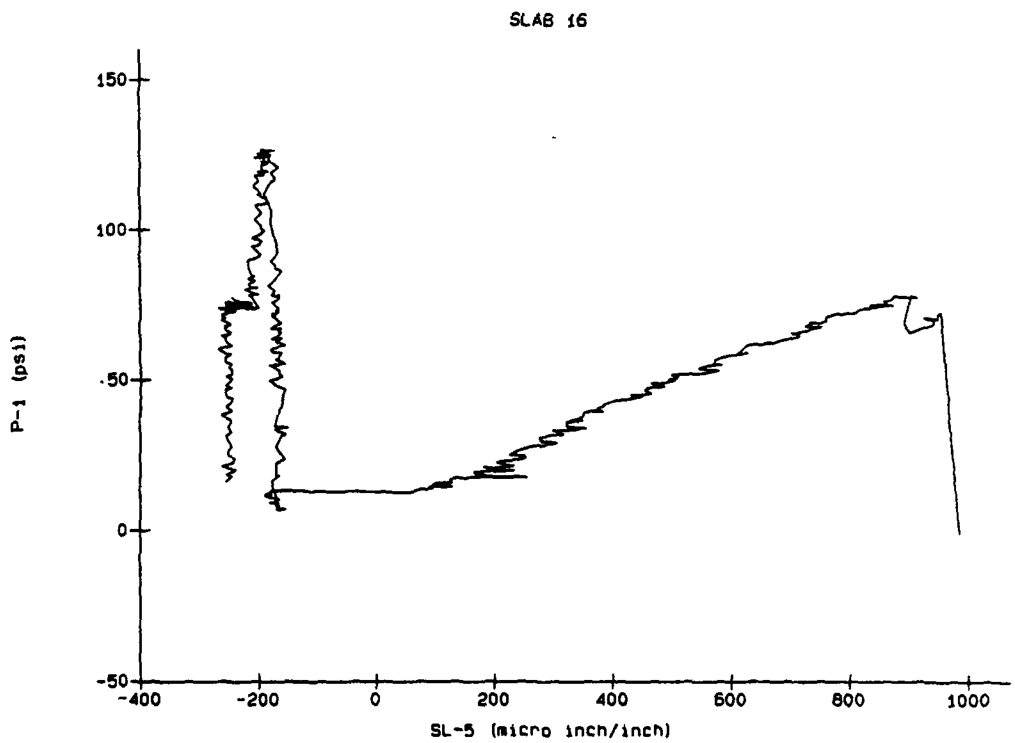
SLAB 16




SLAB 16
P-1 (psi)
150
100
50
0
-50
-3500
-3000
-2500
-2000
-1500
-1000
-500
0
500
1000
1500
SL-2 (micro inch/inch)


SLAB 16
P-1 (psi)
150
100
50
0
-50
50
100
150
200
250
300
350
400
450
SL-3 (micro inch/inch)


SLAB 16
150
100
50
0
-1000
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
P-1 (psi)
SL-4 (micro inch/inch)


SLAB 16
150
100
50
0
-50
-400
-200
0
200
400
600
800
1000
P-1 (psi)
SL-5 (micro inch/inch)